LHC searches for new Physics and Dark Matter

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Lecture ideas & goals

- *LHC physics and experiments + results* is a extremely wide field
- Lecture concentrates on explaining the (basic) relevant physics of LHC & searches for physics beyond the Standard Model
- Provide <u>up-to-date</u> (summer 2017) knowledge about LHC physics & LHC results

➔ Knowledge of what is going on and planned at the LHC

➔ Provide ability to follow typical recent LHC discussions & LHC talks

OUTLINE for this week

- **Part A: Tuesday**
- - 1. **Reasons** to go Beyond the Standard Model
- - 2. Experimental **techniques**
- **Part B: Wednesday**
- - 3. Brief overview **Higgs** physics
- - 4. SM backgrounds and **Searches** for Physics beyond the Standard Model, including introduction to Supersymmetry

Part 1-
Physics Beyond the SM

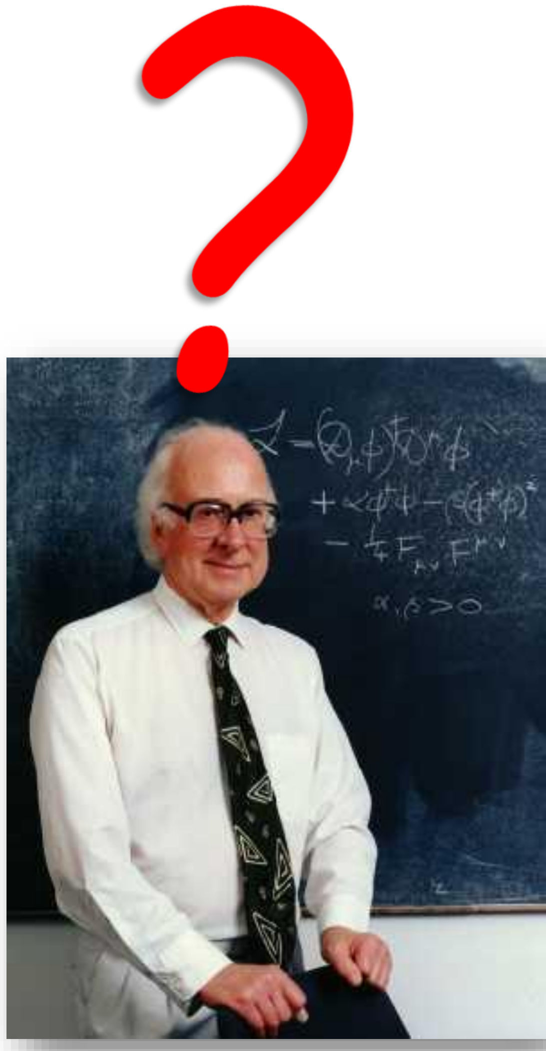
“…A bit longer introduction…”

- 5 min. Standard Model and shortcomings
- Reasons for physics beyond the SM
- Hierarchy problem
- Dark Matter particles (in 2 min, see other lectures)

Part 2- Experimental techniques

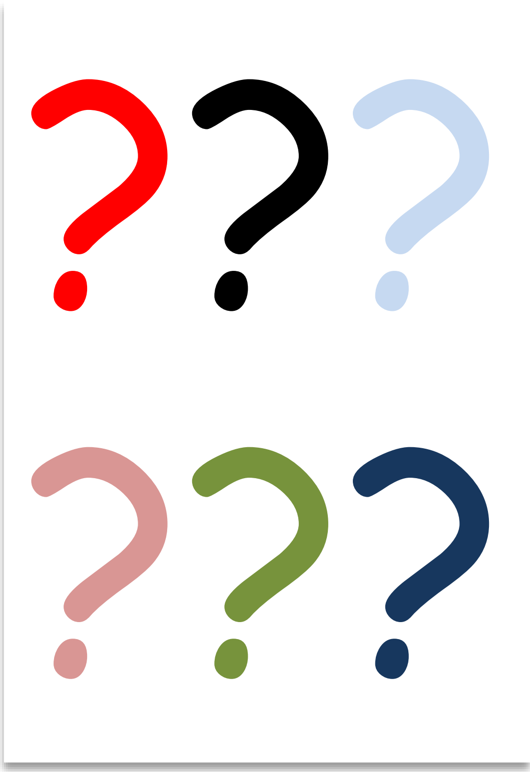
- LHC machine
- Proton-proton collisions
- Cross sections, perturbation theory and event generation
- Triggering
- LHC detectors
- Particle Identification (20 slides extra at the end of the talk, if interested)

Part 3 – Higgs physics



- If time allows …

Part 4 – BSM Searches



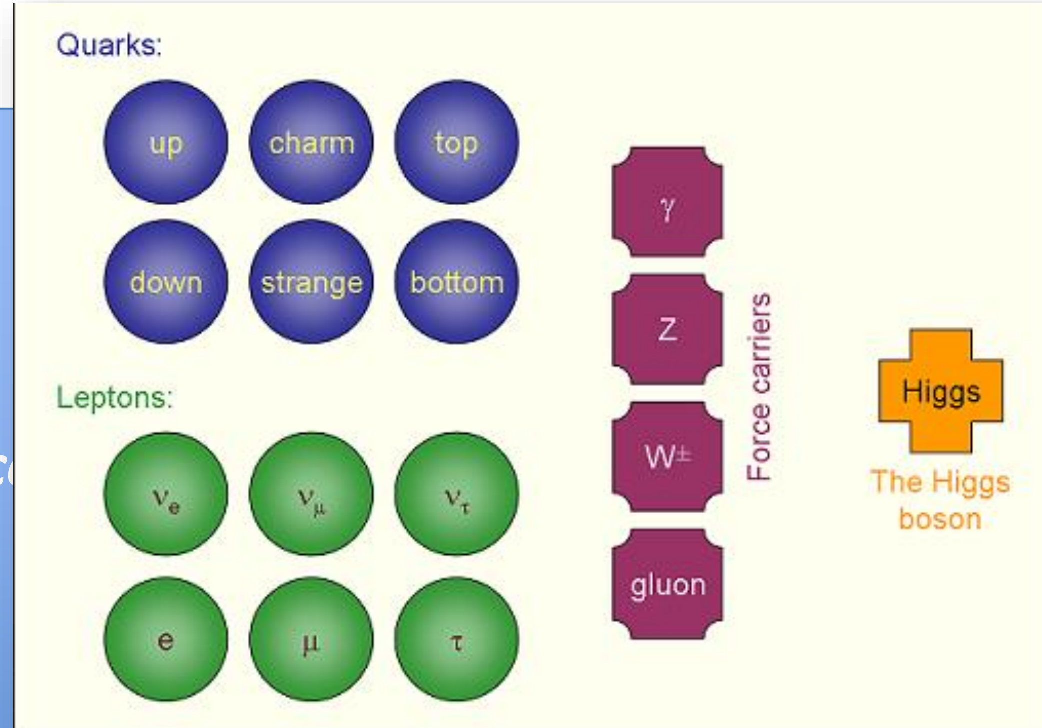
- Supersymmetry
- Dark Matter searches
- Effective field Theory approaches
- “simplified models”
- Where are we now ? Future prospects

Part 1:

Standard Model and beyond

The Standard Model of Particle Physics

Standard Model reminder

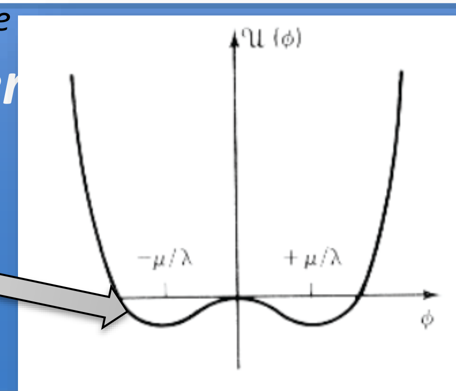


QFT is invariant under a <u>local</u> change of gauge
➔Massless force carriers (spin 1 bosons) for the *electroweak and the strong forc*

But the W and Z bosons are massive!

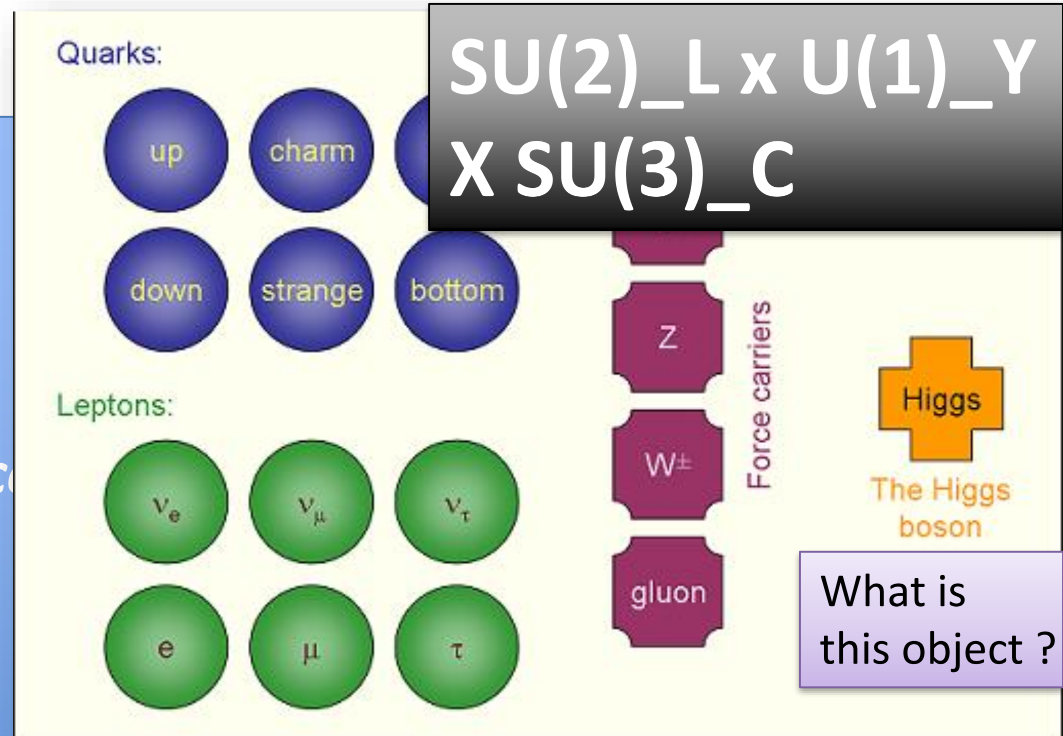
Problem is solved by Higgs mechanism:
➔*Mass of W and Z only generated after transformation into a ground state of the syster*
(electroweak symmetry breaking)

Or Englert-Brout-Higgs-Guralnik-Hagen-Kibble



<u>Predicts observable Higgs boson with spin 0</u>

Standard Model reminder



SU(2)_L x U(1)_Y X SU(3)_C

What is this object ?

QFT is invariant under a <u>local</u> change of gauge
→Massless force carriers (spin 1 bosons) for the *electroweak and the strong forc*

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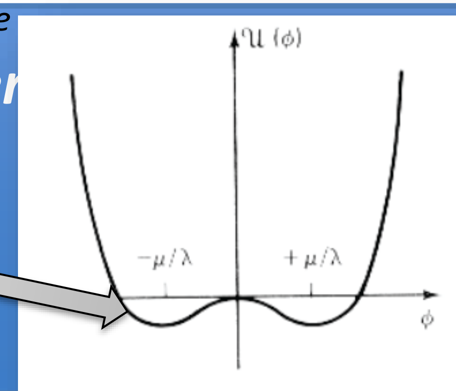


<u>Predicts observable Higgs boson with spin 0</u>

Motivations for BSM

- SM shortcomings (charge quantization, seesaw mechanism) → BSM searches
- Hierarchy problem → BSM/SUSY searches
- Antimatter problem → extra CP violation
- Neutrino masses and flavors: Why different to Lepton flavors ? → LPV violation
- Higgs: What exactly is the Higgs field? → Higgs measurements
- Dark matter → DM / SUSY etc. searches

Shortcomings: example

- Why q_e = - q_proton ?
- Or: Why q_e = -1/3 q_down = 2/3 q_up ?
- Or: Why q_electron = q_muon = q_tau ?

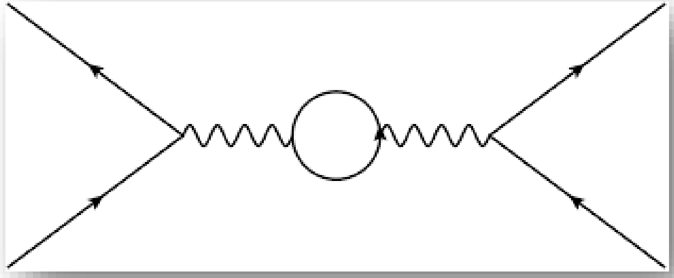
➔Charge quantization is not described in the SM.

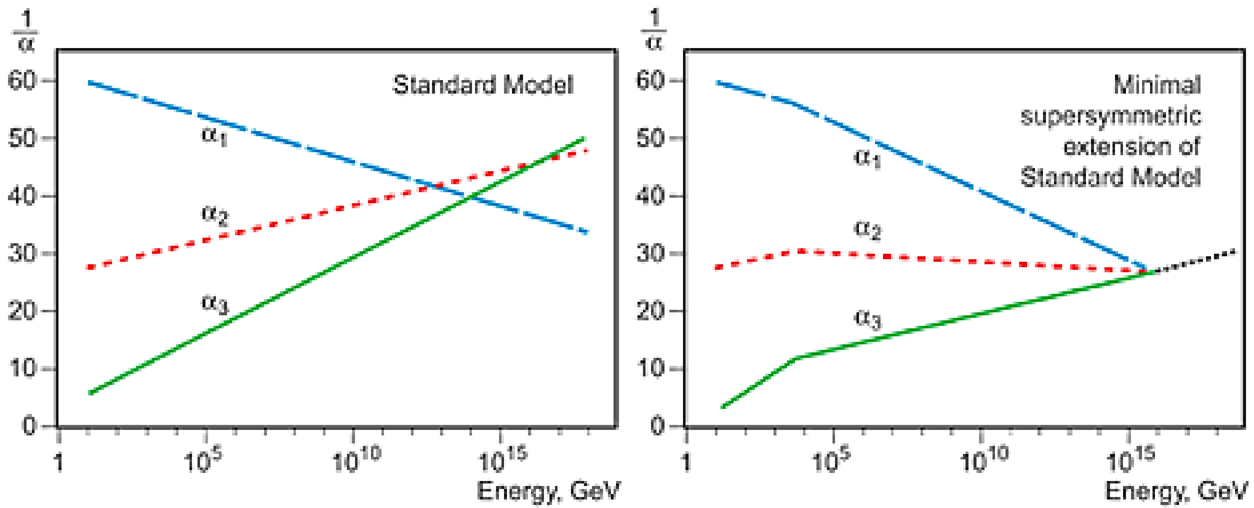
➔Charge structure per family is needed to prevent so called loop anomalies

➔Charge quantisation could be the result of a larger group structure at very high energies

Scales of new physics: Coupling constants

Renormalization of vacuum polarization diagrams ➔ coupling constants are energy dependent





➔ Assume a unification scale (Grand Unified Theory, GUT) at around 10^14-10^16 GeV
➔ Old idea: SU(5) group yields to fast proton decay
➔ excluded already (not excluded if SUSY GUT)

Scales of new physics: Remember Gravity

- At M=1,22 * 10^18 GeV Gravity becomes large :
  ➔ Planck Scale

Gravity potential $\approx$ comparable to particle rest energy

$$G\frac{M^2}{r} \approx Mc^2$$

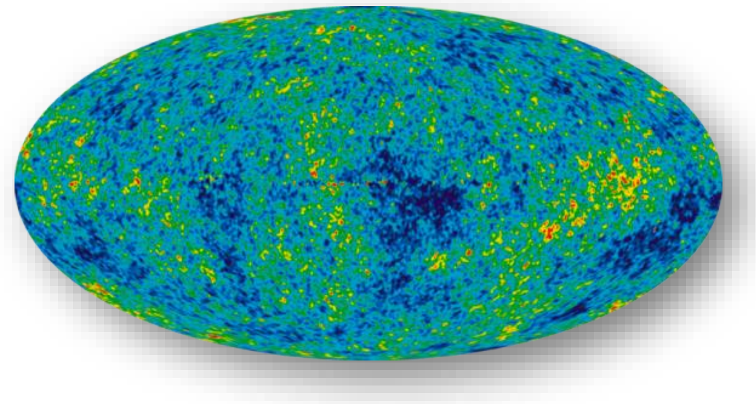
and $r =$ natural unit of length for particle mass M (Compton Wavelenght)

$$r = \frac{\hbar}{Mc}$$

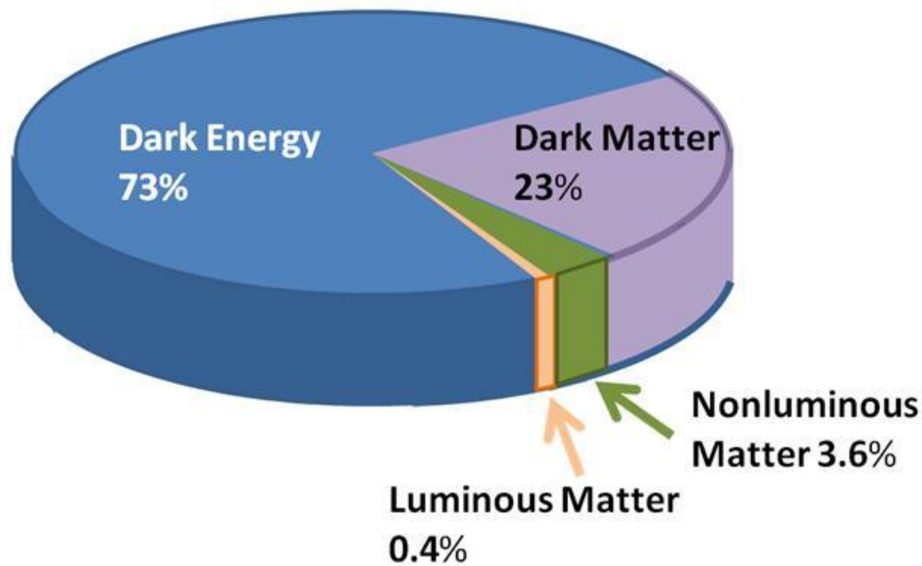
$$\Rightarrow \quad G\frac{M^3 c}{\hbar} = Mc^2$$

➔ Not that far away from GUT scale ➔ Unification of all 4 forces with a Planck scale theory (Quantum Gravity…)

What could be the DM ?



Lambda **CDM**
(Cold / non relativistic Dark Matter)
model
is the state-of-the art



CDM still problems with short scale structure, but alternatives seem to be even worse…

Conditions for Dark Matter candidate

- “Massive” (otherwise no cold DM)
- Electrically neutral
- Correct relic DM density (Omega*h2 = 0.1)
- Stable (on today scales)

➔ Lambda-CDM model requires self-annihilation of DM in early Universe (in thermal equilibrium) with cross section for right relic DM density

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3\, \mathrm{s}^{-1}$$

DM at the LHC ?

- If DM couples too weakly *(e.g. Axions, sterile neutrinos)*

  ➔ **<u>No chance for LHC</u>**

LHC only sensitive if coupling via “weak interactions” (or new messenger particle) : **W**eakly **I**nt. **M**assive **P**article

- If we assume a “weak interaction” for self-annihilation of $\langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

  ➔ Dark Matter Particle mass of around 100 GeV yields correct relic density !

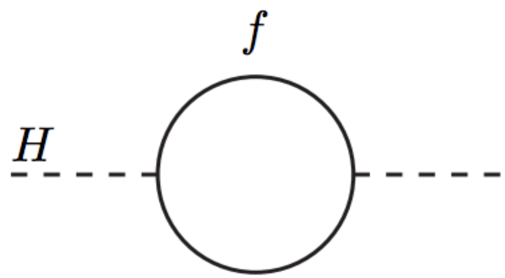
  ➔ This is the **electroweak** scale ! (WIMP miracle)

  ➔ Such particles **would** be produced at LHC (remember the Higgs!)

More reasons/conditions for physics beyond the Standard Model and new particles

→ Hierarchie problem

Hierarchy problem



(a)

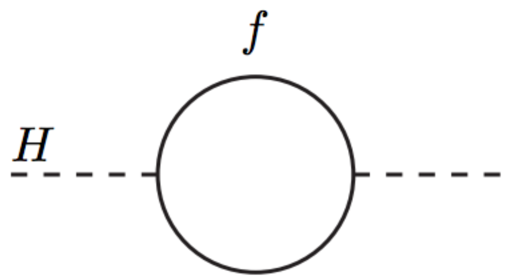
Yields quadratic divergence to the higgs mass:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots .$$

➔ Literature not sure if this is a problem already (in pure SM). If scale is arbitrary or so called dimensional regularisation is imposed Divergency can be absorbed into the definition of m_h

➔ However we know that we NEED physics BEYOND THE SM !

Hierarchy problem



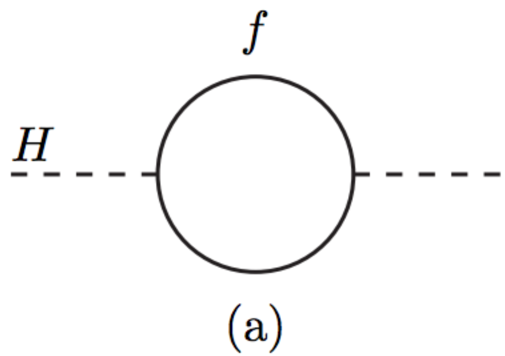
(a)

Yields quadratic divergence to the higgs mass:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \ldots .$$

➔ Then the scale lambda is not arbitrary and also dim. Regularisation Shows terms which have size of Lamda^2 (for particles at scale Lambda coupling to the Higgs)

Hierarchy problem



Yields quadratic divergence to the higgs mass:

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots .$$

Hierarchy problem can be seen as a condition for any new BSM theory. Theory should be such that is does not contribute dangerously to the Higgs mass

Hierarchy problem -> Interesting solution

Unbroken Supersymmetry: $$\Delta m_H^2 = \frac{1}{8\pi^2}(\lambda_S - |\lambda_f|^2)\Lambda_{\mathrm{UV}}^2 + \ldots .$$

And: $$\lambda_S = |\lambda_f|^2$$

Fine tuning problem

Every beyond the SM theory “coupling”
to any of the SM particles and defined at the scale Λ will contribute to the Higgs mass:

Higgs Mass = X + Quantum Corrections (Λ)

Fine tuning problem

Higgs Mass = X + Quantum Corrections (Λ)

Solution 1: New physics at Planck scale coupling to SM

Λ = 10^18 GeV

125 GeV = X + 123456789123456789 GeV

Conclusion X needs to be highly **“fine tuned”** to get the right Higgs mass !

➔ **Unnatural**

➔ **Highly dependent on correct choice of input parameters**

➔ **Also highly dependent on choice of any other SM parameters !**

Fine tuning problem

Higgs Mass = X + Quantum Corrections (Λ)

Solution 2: New physics at TeV scale coupling to SM

Λ = 10^3 GeV

125 GeV = X + 1000 GeV

Conclusion X needs to be very softly **tuned** to get the right Higgs mass.
→Natural ?
… but how natural precisely given no new particles at LHC ?

Fine tuning in Supersymmetry

Higgs mass = Z mass + Quantum Corrections (M_SUSY)
125 = 91 + Quantum Corrections (M_SUSY)

Fine tuning of Higgs mass can be rewritten in fine-tuning of Z mass

Z mass = Higgs mass – Quantum Corrections (M_SUSY)

How large is the fine-tuning of the MSSM?

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

PART 2 :

Experimental techniques

Particle Accelerators

- LEP: colliding electrons and positrons, i.e. pointlike particles
- LHC/Tevatron: colliding protons (LHC) or protons on antiprotons

Why building proton colliders ? Synchrotron radiation

- Energy loss per turn (2 GeV at LEP-2)

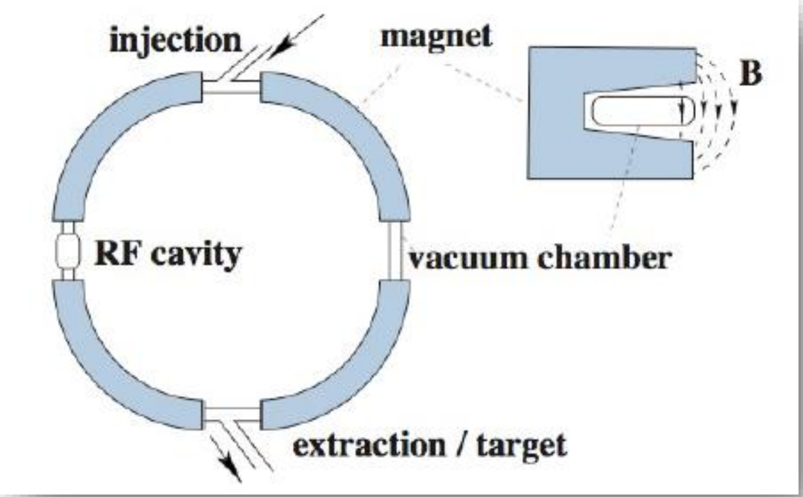
$$-\Delta E \approx \frac{4\,\pi\,e^2}{3\,R}\left(\frac{E}{mc^2}\right)^4$$

- Ratio of the energy loss between protons and electrons:

$$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$

➔A linear electron/positron accelerator is a solution
Here the maximum energy is prop. to length
➔Very expensive to build multi-TeV machine

Hadron Colliders



Advantage of hadron collider:
-Small energy loss, possible
to build synchrotron

p = R e B

Increase bending field
synchronous with
momentum gain → constant radius

Disadvantages of hadron colliders:
-Non-pointlike collisions
-longitudinal momentum of colliding particles unknown
-complex collisions due to QCD effects

- LHC as discovery machine to explore high energy regime
- Later a linear collider is needed to understand
more of the details of what we might have found

Accelerators at the Energy Frontier

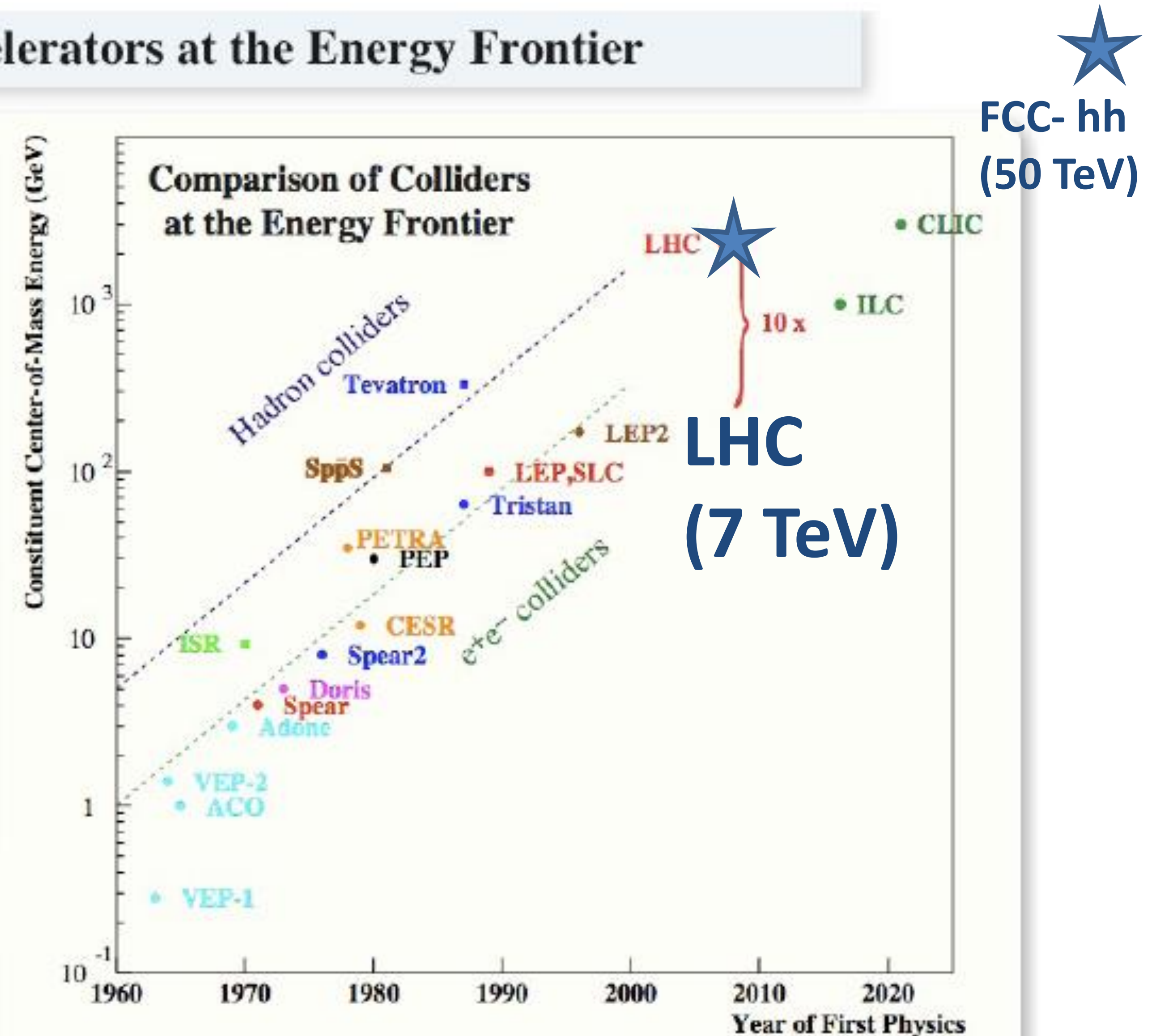
Livingston plot

Exponential growth of E_{cms} in time

Starting in 60's with e^+e^- at about 1GeV

Factor 4 every 10 y

$pp, p\bar{p}$: $E_{cms}/6$ still 5 × above e^+e^- at same time



$pp, p\bar{p}$: discovery machines
e^+e^- : precision machines
both required

The LHC which starts now is a big step forward
Excellent potential for major discoveries

The Charged Particle Beam

- The accelerator generates, accelerates, transports and delivers beams to the user (e.g. HEP exp).
- Beam are transported in ultra-high vacuum.
- A beam can consist of individual bunches.
- Each “bunch” is an ensemble of charged particles that are grouped together in space and carry the same (very similar) energy.
- Radio-frequency fields are used to accelerate particles coherently and to group them together longitudinally.
- Magnetic fields are used to guide the beam particles on well defined paths and to focus them into a small transverse area.

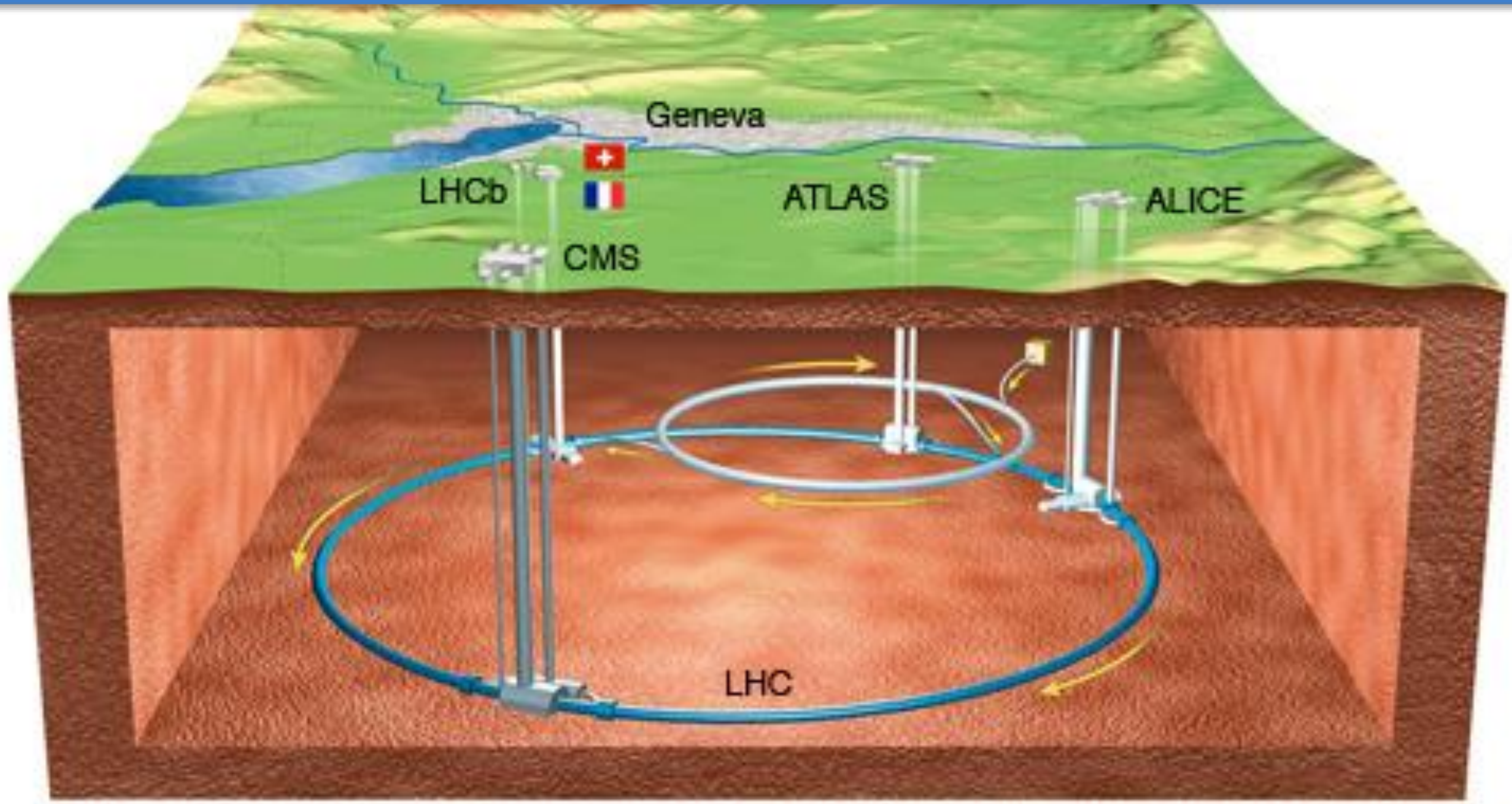
The Large Hadron Collider (LHC)

Accelerator type : Synchrotron   Approved : 1994-96

First Collisions: 2009 at 900 GeV , 2010-2013 at 7 TeV in pp , 2015 at 13 TeV in pp
2.76 TeV per nucleon in Pb Pb

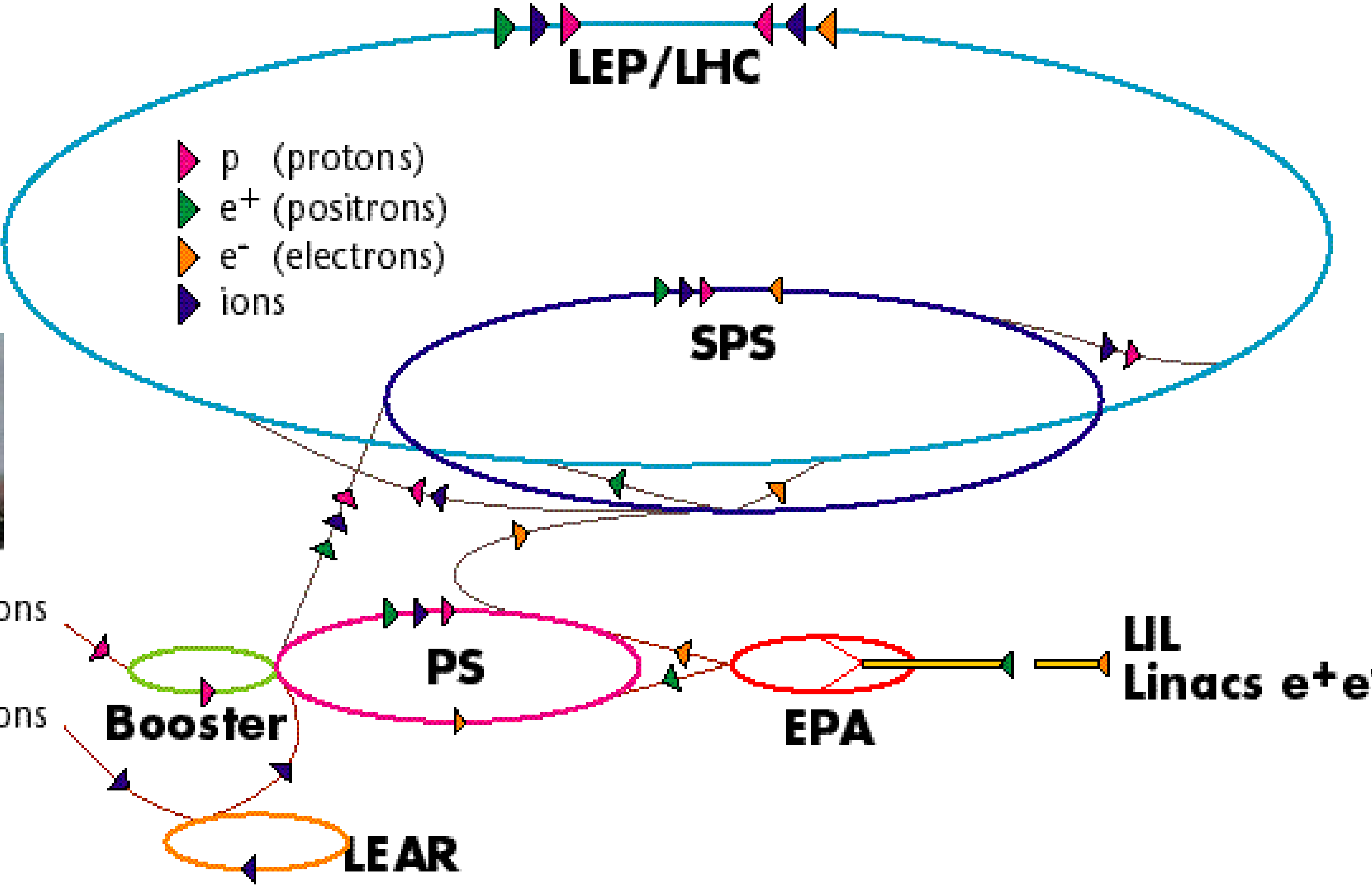
Length: 27 km and up to 70-140 m underground

Energy stored in LHC in design operation : >1 Gigajoule (about energy of ICE train)



Producing the LHC beams

H gas

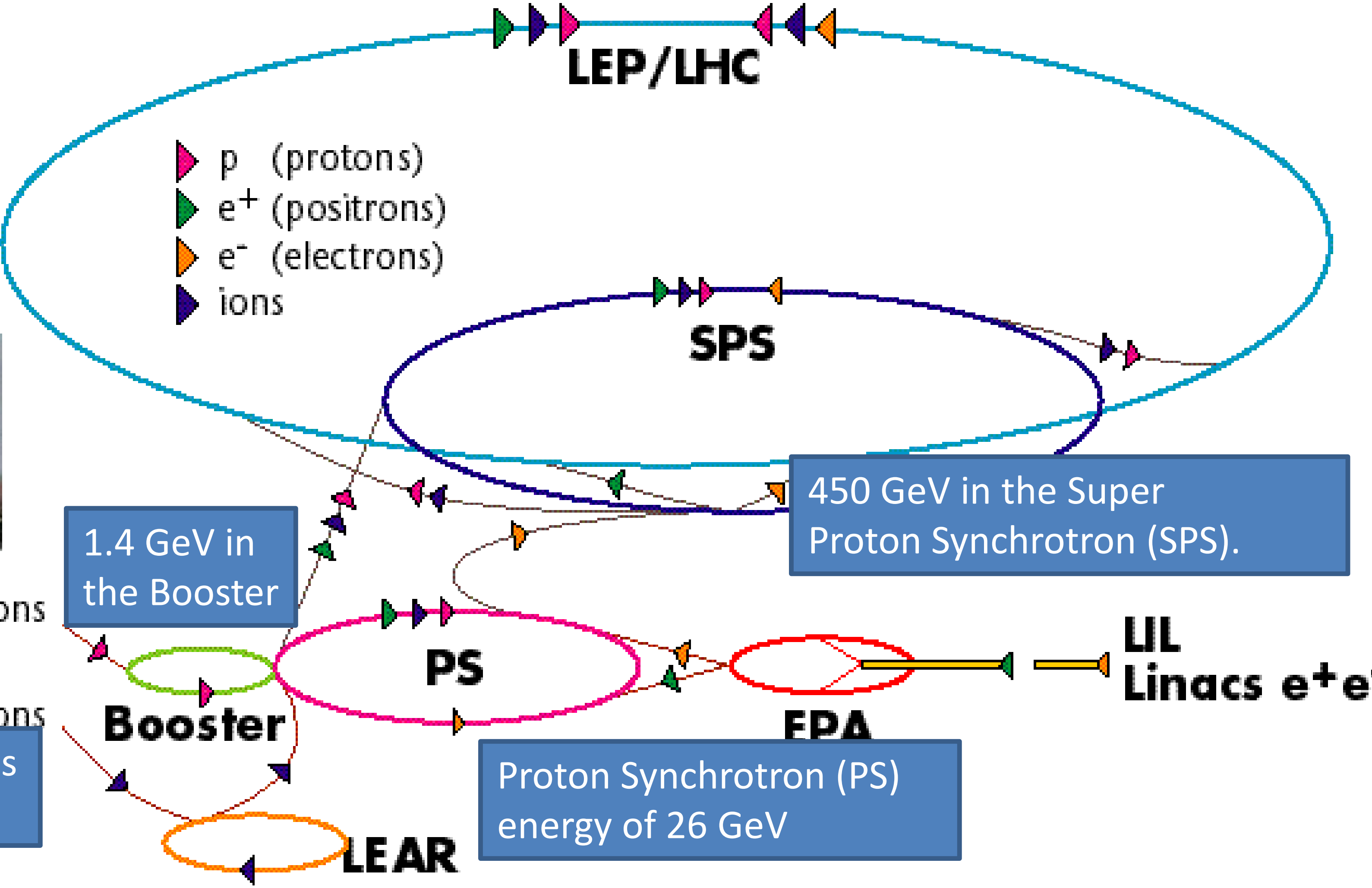


LIL : LEP's Linac Injector
EPA : Electrons-positrons Accumulator
PS : Proton Synchrotron
SPS : Super Proton Synchrotron

LEP : Large Electron-Positron Collider
LHC : Large Hadron Collider
LEAR : Low Energy Accumulator Ring

Producing the LHC beams

P produced From H gas



1.4 GeV in the Booster

450 GeV in the Super Proton Synchrotron (SPS).

50 MeV protons in the LINAC

Proton Synchrotron (PS) energy of 26 GeV

LIL	: LEP's Linac Injector	LEP	: Large Electron-Positron Collider
EPA	: Electrons-positrons Accumulator	LHC	: Large Hadron Collider
PS	: Proton Synchrotron	LEAR	: Low Energy Accumulator Ring
SPS	: Super Proton Synchrotron		

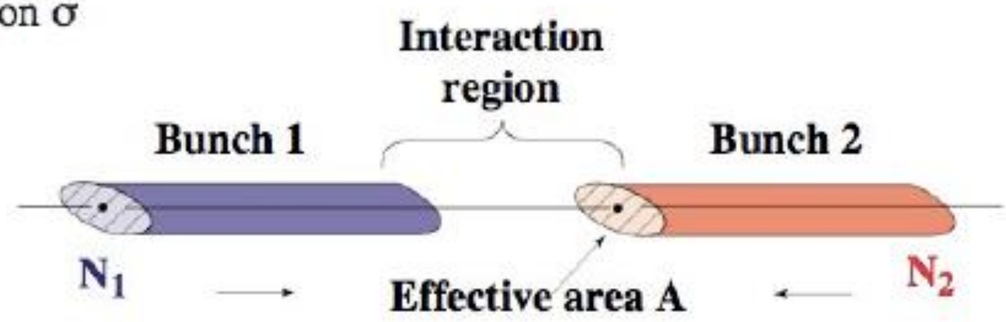
Event rate and luminosity

Event rate for process with cross section σ

$$\dot{n} = \mathcal{L}\sigma$$

Instantaneous
Luminosity from bunch crossings at frequency $f = f_{rev}\, n_b$

$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$



for Gaussian bunches with rms sizes $\sigma_x\ \sigma_y$ $\quad A = 4\pi\sigma_x\sigma_y$

Cross sections for interesting processes can be tiny

➔We need a large instantaneous luminosity to produce interesting events at a high rate

➔We need a large number of particles per bunch **N**, a large number of bunches $\mathbf{n_b}$ colliding in a small effective area **A** (➔strong focusing)

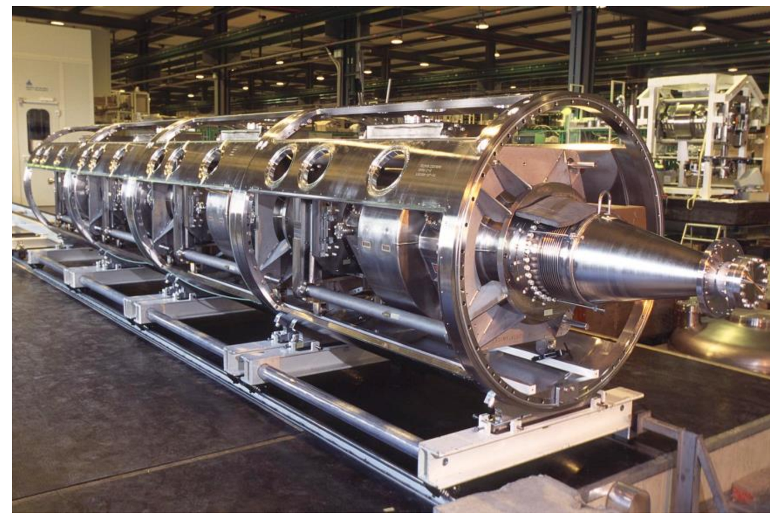
LHC acceleration and focussing

Accelerate the beam: Radiofrequence (RF) acceleration

Done with super conducting cavities

Field adjustable (from 0.99c to 0.999c to…)

Allows multiple passages



400 MHz system:

16 cavities (copper sputtered with niobium) for 16 MV/beam built and assembled in four modules

Focus the beam: Quadrupole magnets

focus in one coordinate and defocus in the other coordinate

and a 2nd Quadrupole to do this

vise versa + corrector magnets

➔ Beam squeezed in $\sigma_{x,y}$ from about 0.2 mm to 17 μm

The LHC – Bending the beam

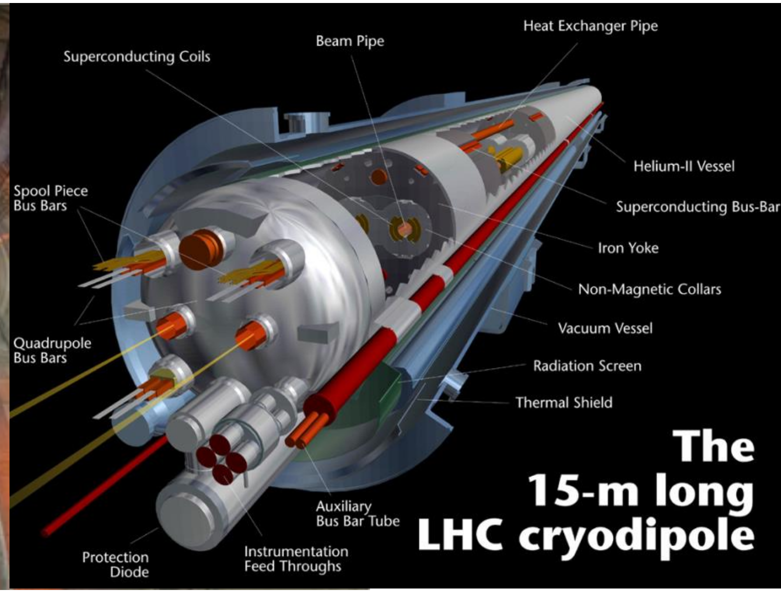
- Particle bending done with superconducting dipole magnets
- To bend a 7 TeV LHC beam through the LEP ring one needs 8.3 Tesla magnets
- The current I to produce this B field (B □ I) is much to large for restive magnets (11800 Ampere)

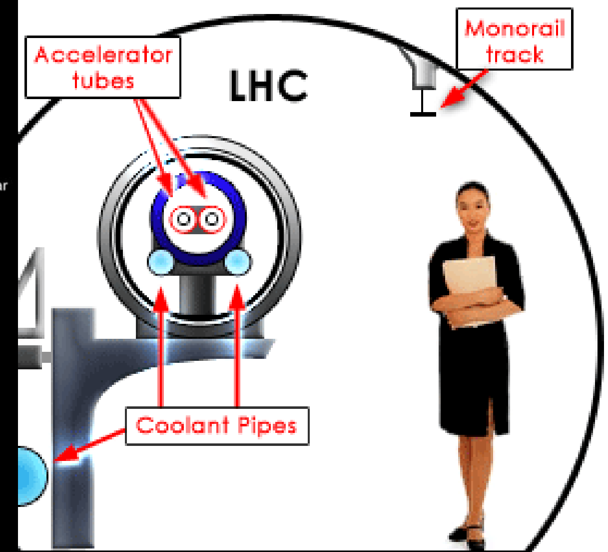
  ➔ resistive magnets would simply melt since power is $P = R*I^2$
- Need for superconducting magnets

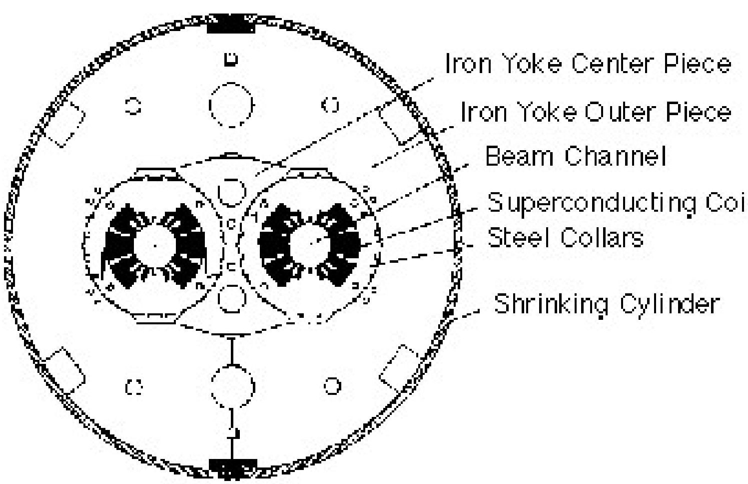
  ➔ Magnets cooled down to 1.7 K (liquid superfluid Helium)

Maximum LHC energy is limited by the maximum dipole field

Inside the LHC







Two-in-One Magnet

Two p beams going in opposite direction need 2 oppositely directed vertical B-fields for bending
➔ two-in-one magnet design

LHC collisions

The luminosity in the LHC is not constant over a physics run, but decays due to the degradation of intensities and emittances of the circulating beams. The main cause of the lumi decay is the beam loss from collisions.

LHC collisions design parameters:

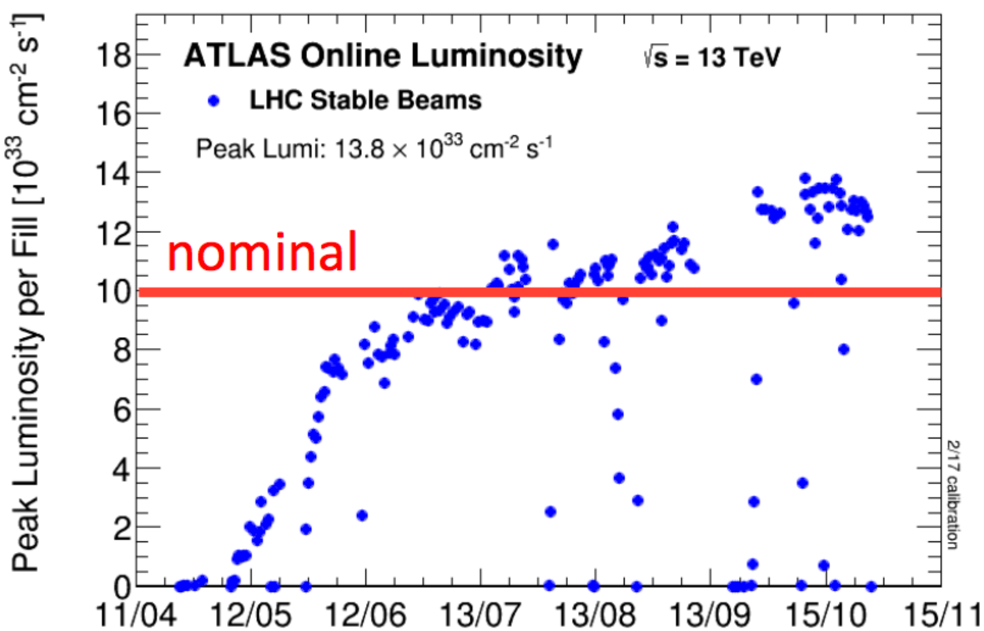
- 2808 bunches for each proton beam (proton needs 90 microseconds to travel around the ring)
- Bunches are separated by 7.5 m and travel with almost c

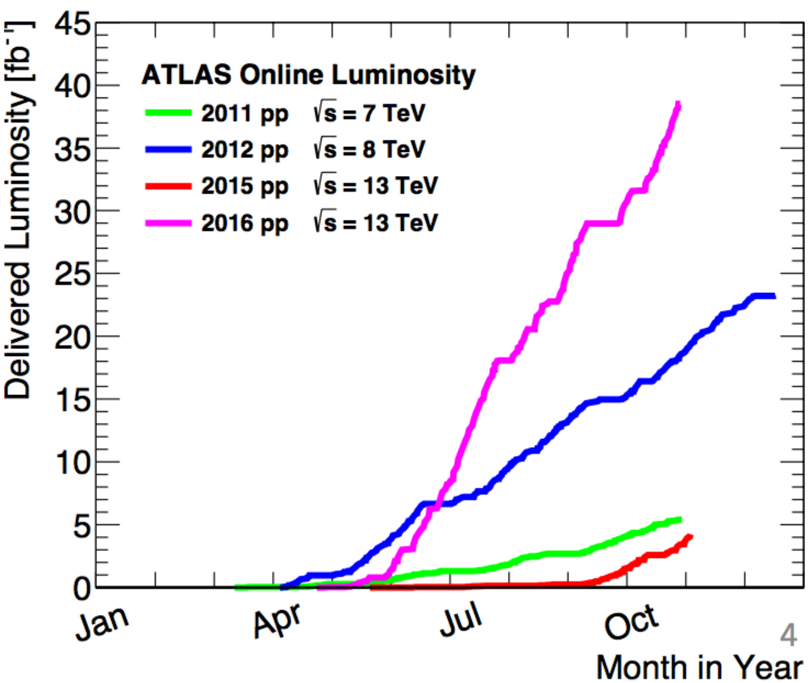
  ➔ bunch crossing every 25 nanoseconds, i.e. with a rate of 40 million Hz
- Up to 20 collisions per bunch crossing

LHC luminosity 2016

13 TeV center-of-mass energy since 2015
Luminosity at **1.4 $\times 10^{34}$**$cm^{-2}s^{-1}$ (better than old nominal 10^{34})

-Better beam understanding of aperture (smaller σ)
-Number of bunches increased at nominal, i.e. 2760 (2017)
-- bunch intensity of **1.1×10^{11}p/bunch**





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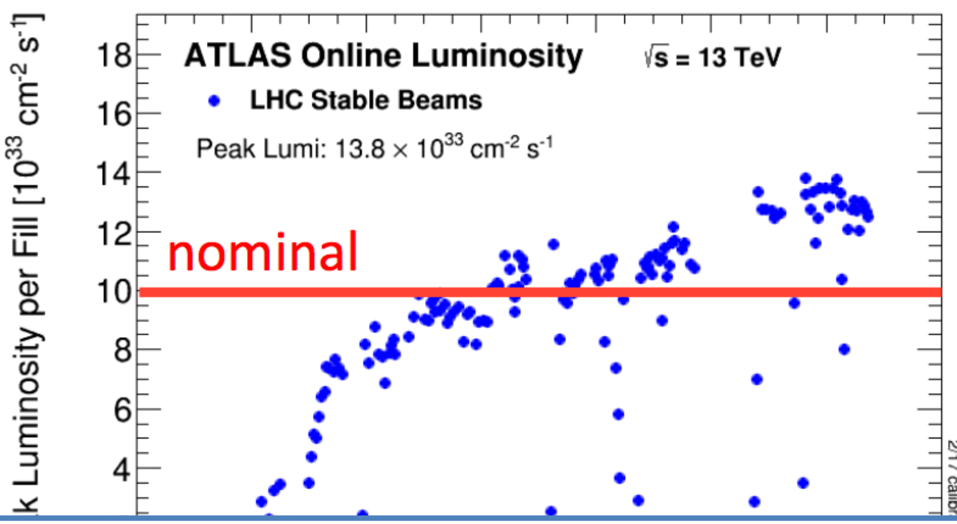
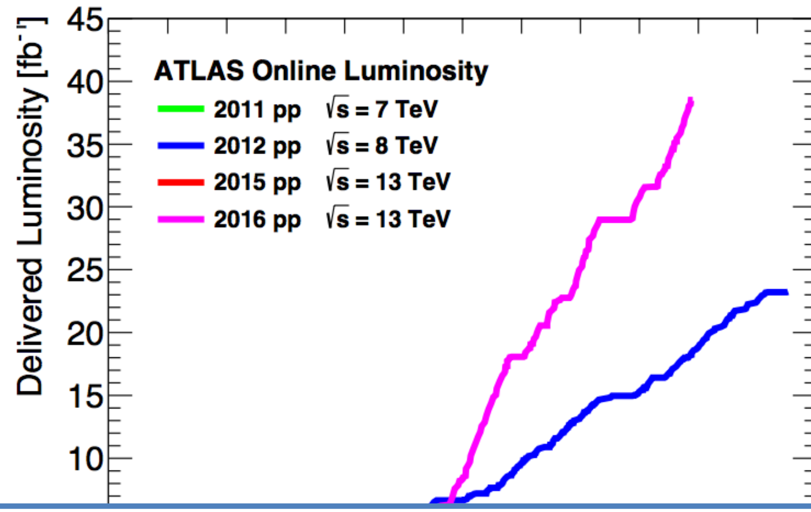
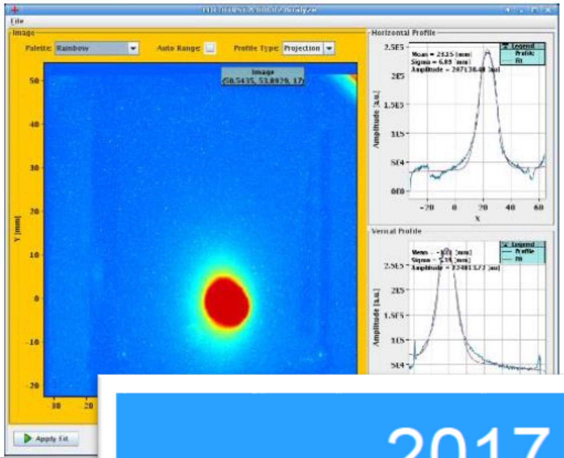
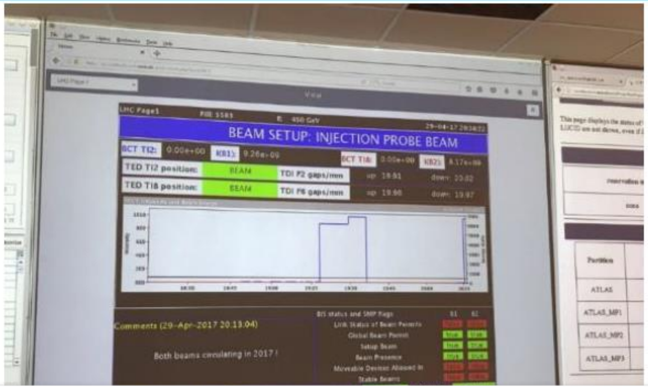




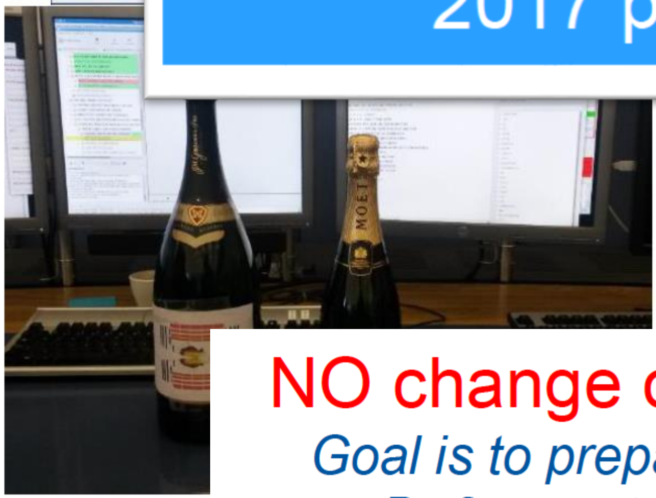
Remember: 1 pb^{-1} = 10^{36} cm^{-2}
1 second at L = 10^{34} cm^{-2}s^{-1} → $\int Ldt$ = 10^{-2} pb^{-1}
1×10h running day at L = 10^{34} cm^{-2}s^{-1} → $\int Ldt$ = 0.36 fb^{-1}

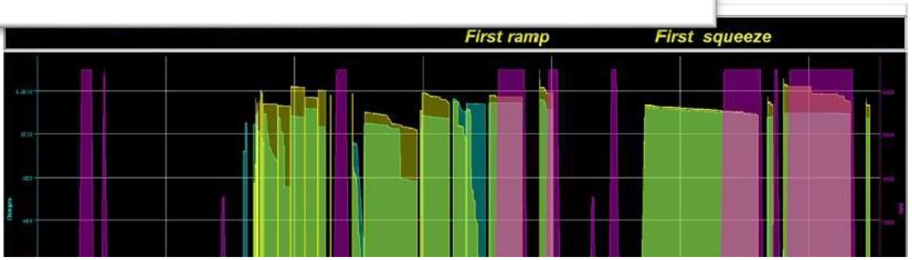
2017: beams are back in LHC from Friday 29th April





2017 plans: $45 fb^{-1}$





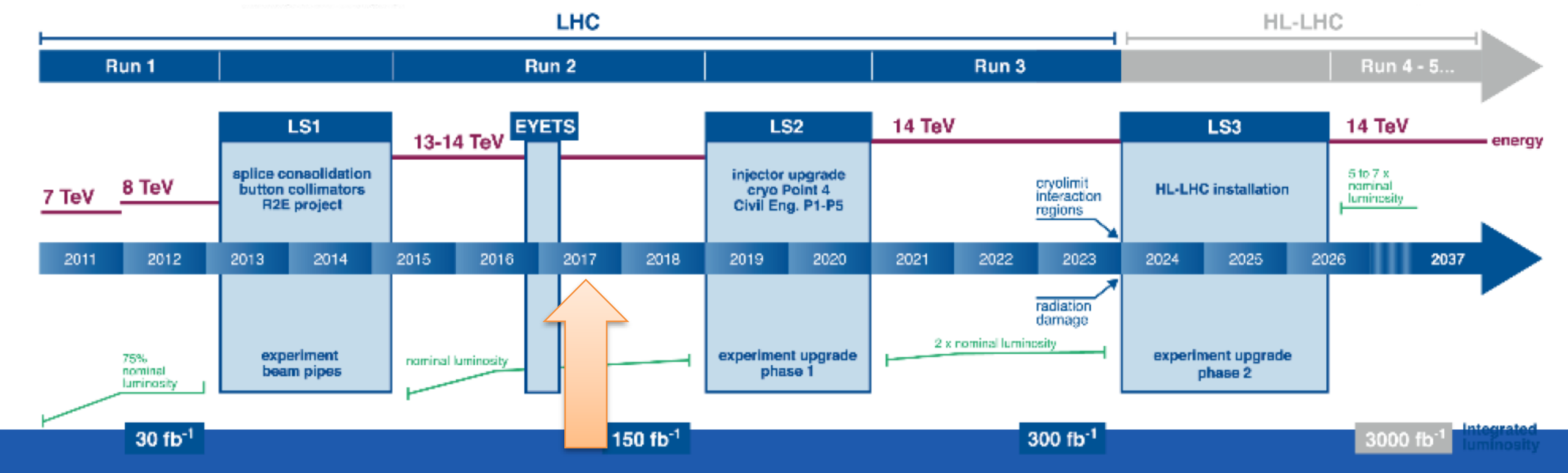
NO change of beam energy in 2017 and 2018

Goal is to prepare the LHC to run at 14 TeV during Run 3.

Preference to make the change in energy in a single step.

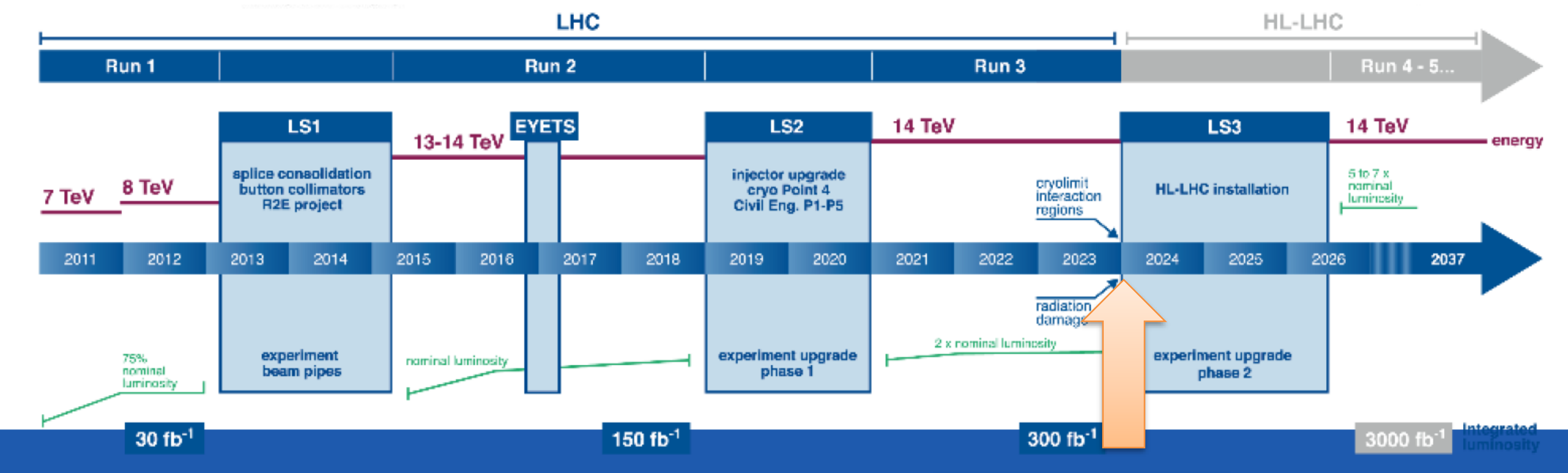
R. Losito, The Large Hadron Collider: status and plans, LHCP 2017

LHC: Longer Term Future



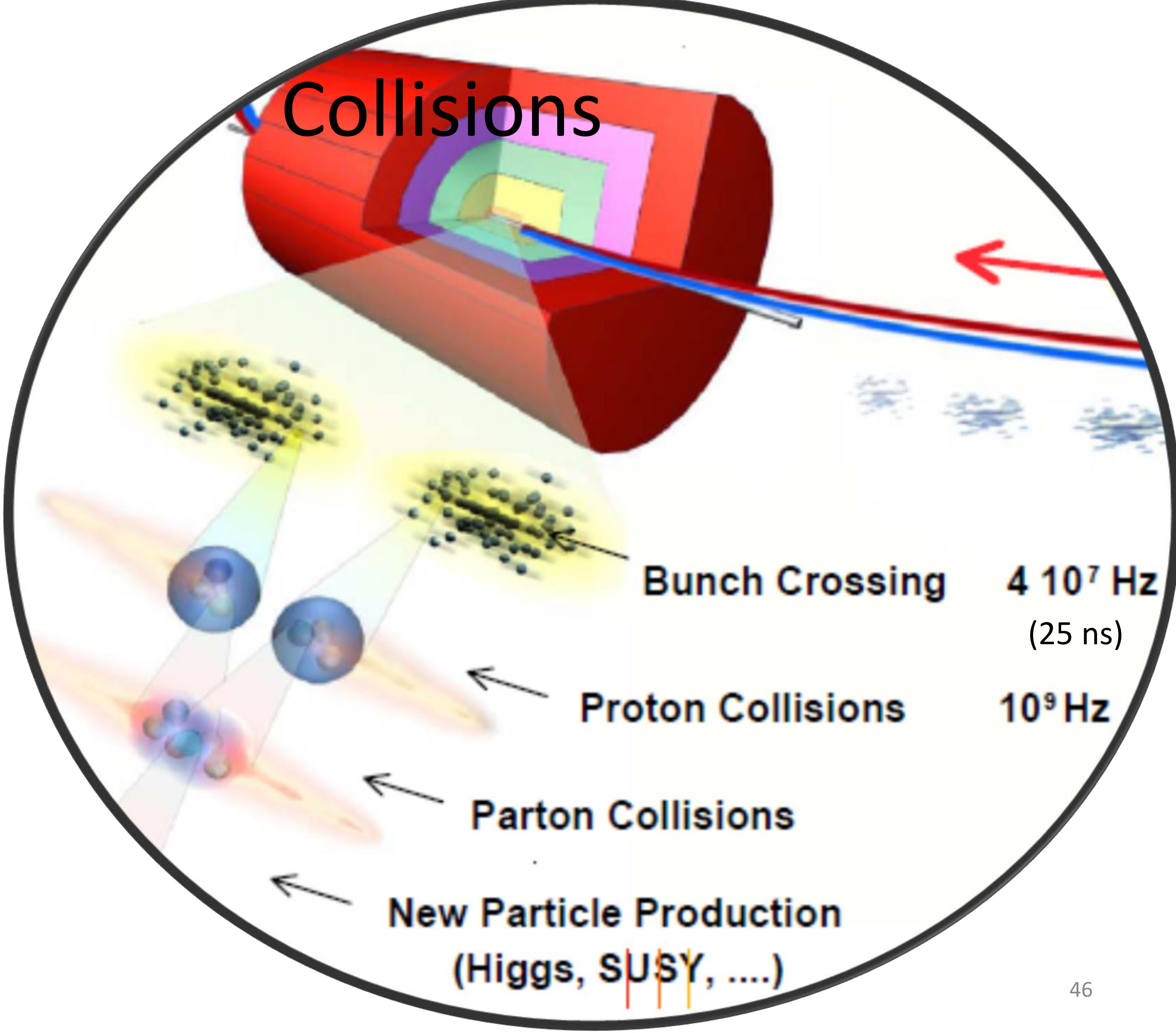
Typically about 3-30 fb-1 analysed as of today

LHC: Longer Term Future

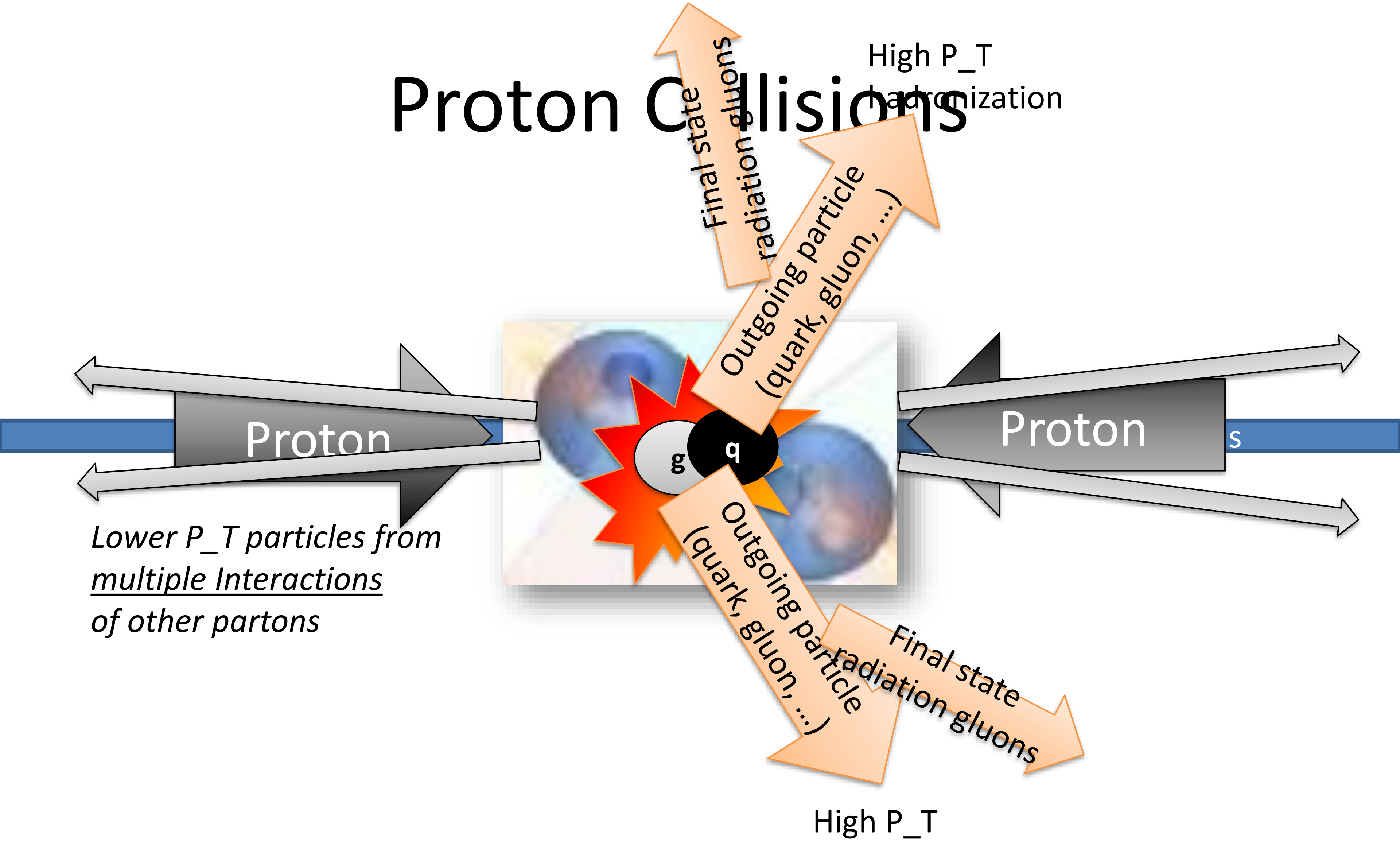


Factor 10 – 100
more data
to be analyzed
in next 5-7 years

Collisions

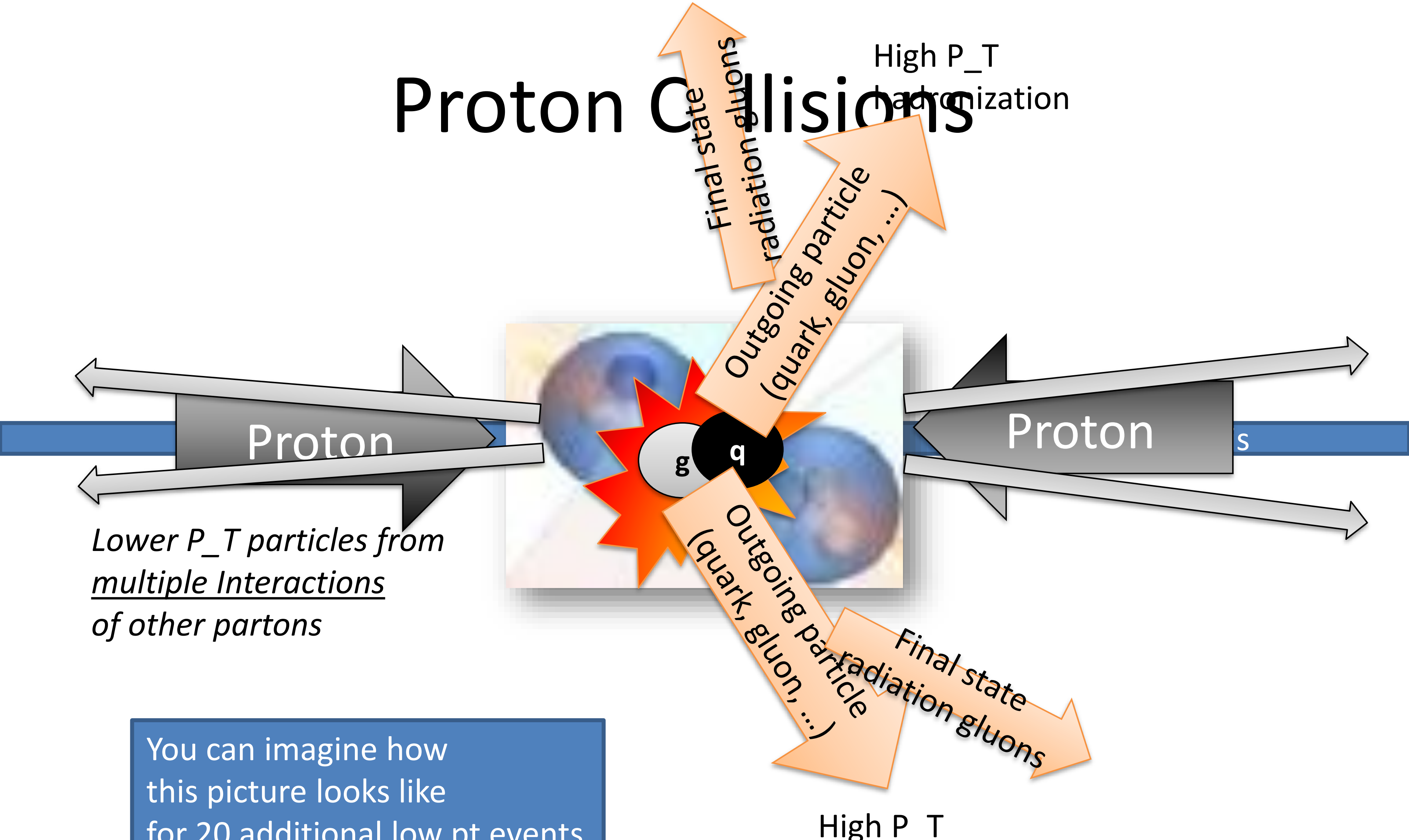

Bunch Crossing 4 10⁷ Hz
(25 ns)
Proton Collisions 10⁹ Hz
Parton Collisions
New Particle Production
(Higgs, SUSY, ...)

Proton Collisions



There are usually many more particles than arrows in this picture

Proton Collisions

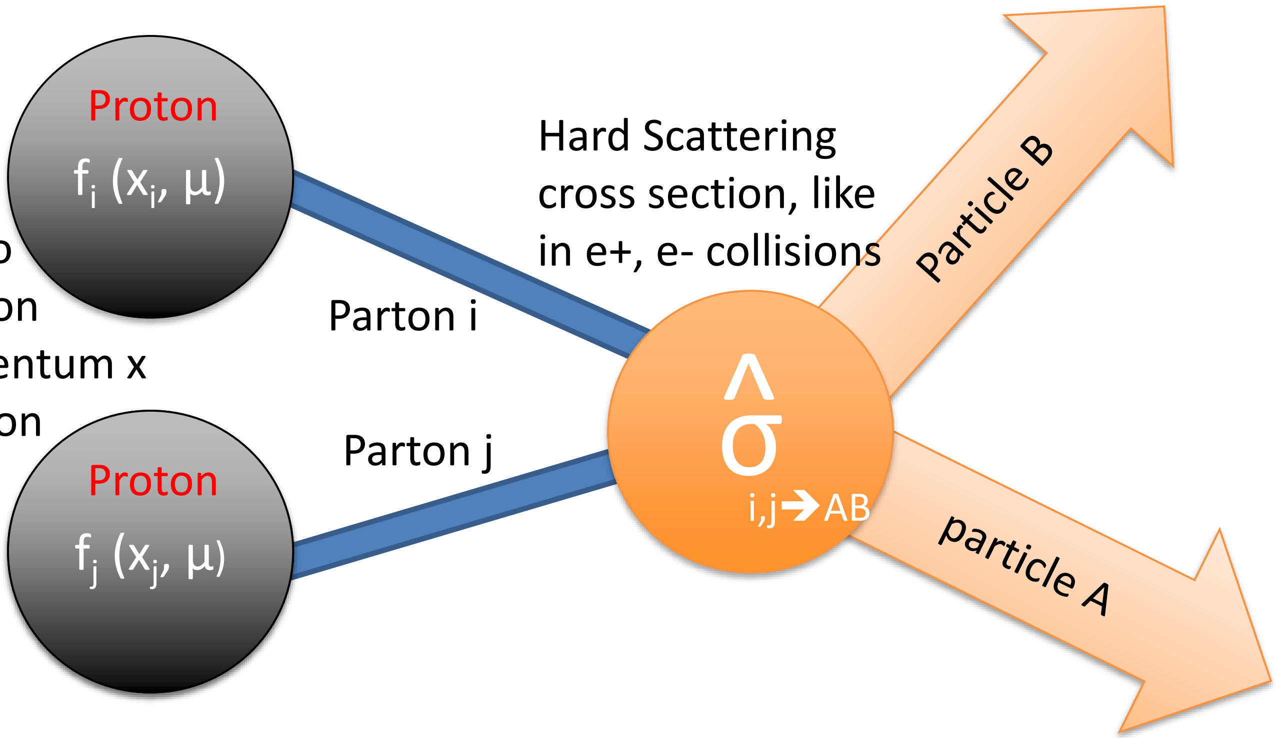


You can imagine how
this picture looks like
for 20 additional low pt events
overlaid to this one

There are usually many more
particles than arrows in this picture

Cross Section

Parton densities: probability densities to find a parton with momentum x in the proton



Cross section for the production of particle A and B

$$\sigma = \sum_{i,j=q,\bar{q},g} \underbrace{\int dx_1 dx_2 \; f_i(x_1, \mu)\, f_j(x_2, \mu)}_{\text{“parton luminosity”}} \; \hat{\sigma}_{i,j \rightarrow AB}(\mu, x_i, x_j, \hat{s})$$

Hard sub-process

- Cross section calculated in perturbation theory
- Expansion in the coupling constants

$$\sigma = \alpha * C_1 + \alpha^2 * C_2 + \alpha^3 * C_3 + \ldots$$

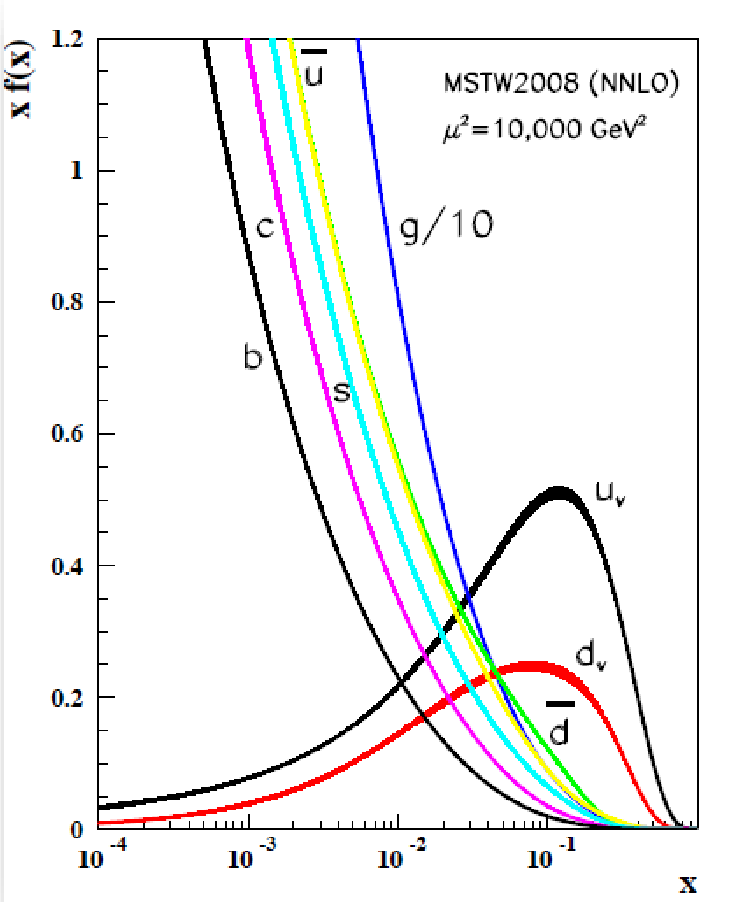
- Largest effect comes usually from QCD

  ➔ Expansion in alpha_strong
- LO : First order
- NLO (next-to-leading-order): 2nd order (virtual + real diagrams contribute)…
- NNLO etc.
- Be aware: NNLO calculation for dijets is only NLO for 3-jet and LO for 4-jet events

Parton densities and LHC

Squared entre-of-mass energy of the hard subprocess

$$\hat{s} = x_1 * x_2 * s$$



A) Higher intergrated luminosity compensates for lower centre-of-mass energy

B) Large Increase especially of gluon density at low x

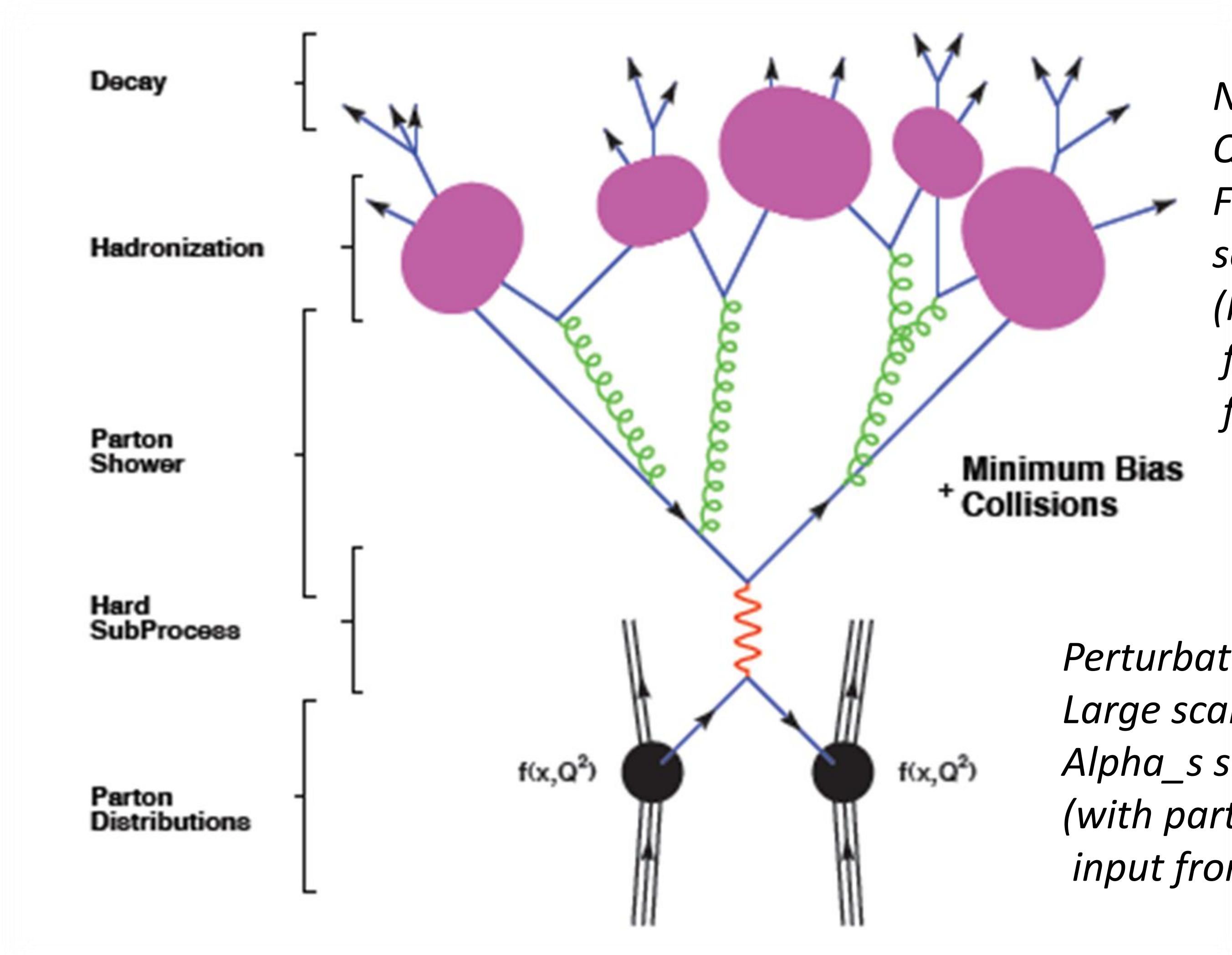
➔Much larger "parton luminosity" at low x

➔Higher centre-of-mass energy compensates for low luminosity (e.g. Tevatron vs LHC)

➔Significant increase in σ for gluon induced processes

Examples are e.g. the early SUSY searches at LHC

Structure of event generation in MC

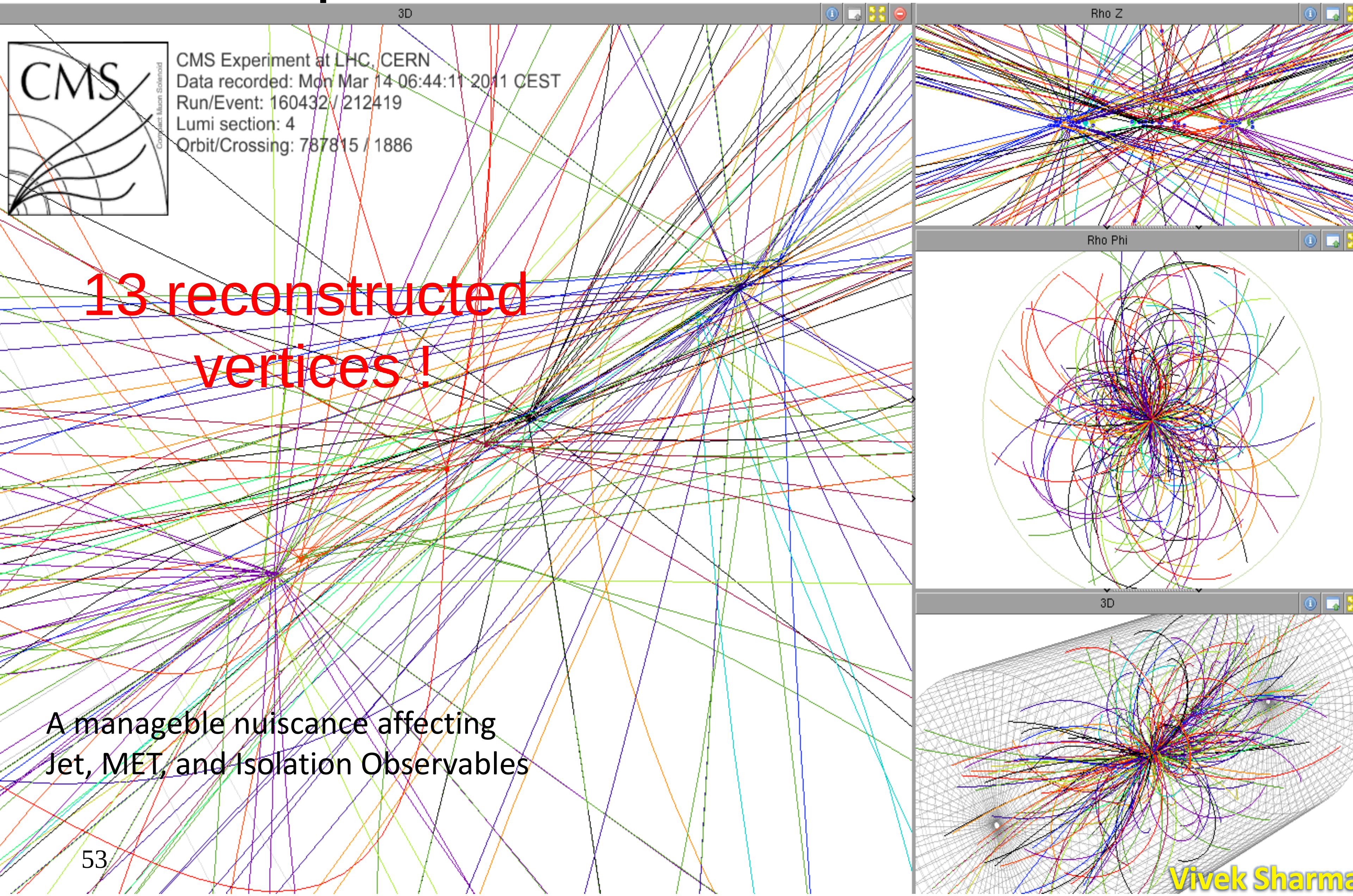


Non-perturbative QCD (hadronization) Final state partons seen as hadrons (Measured fragmentation functions D(z))

Perturbative QCD , Large scales, Alpha_s small (with partly non-perturbative input from pdfs)

Event generation in Monte Carlo programs (some more details tomorrow)

Pileup: A New Feature in 2011 Data

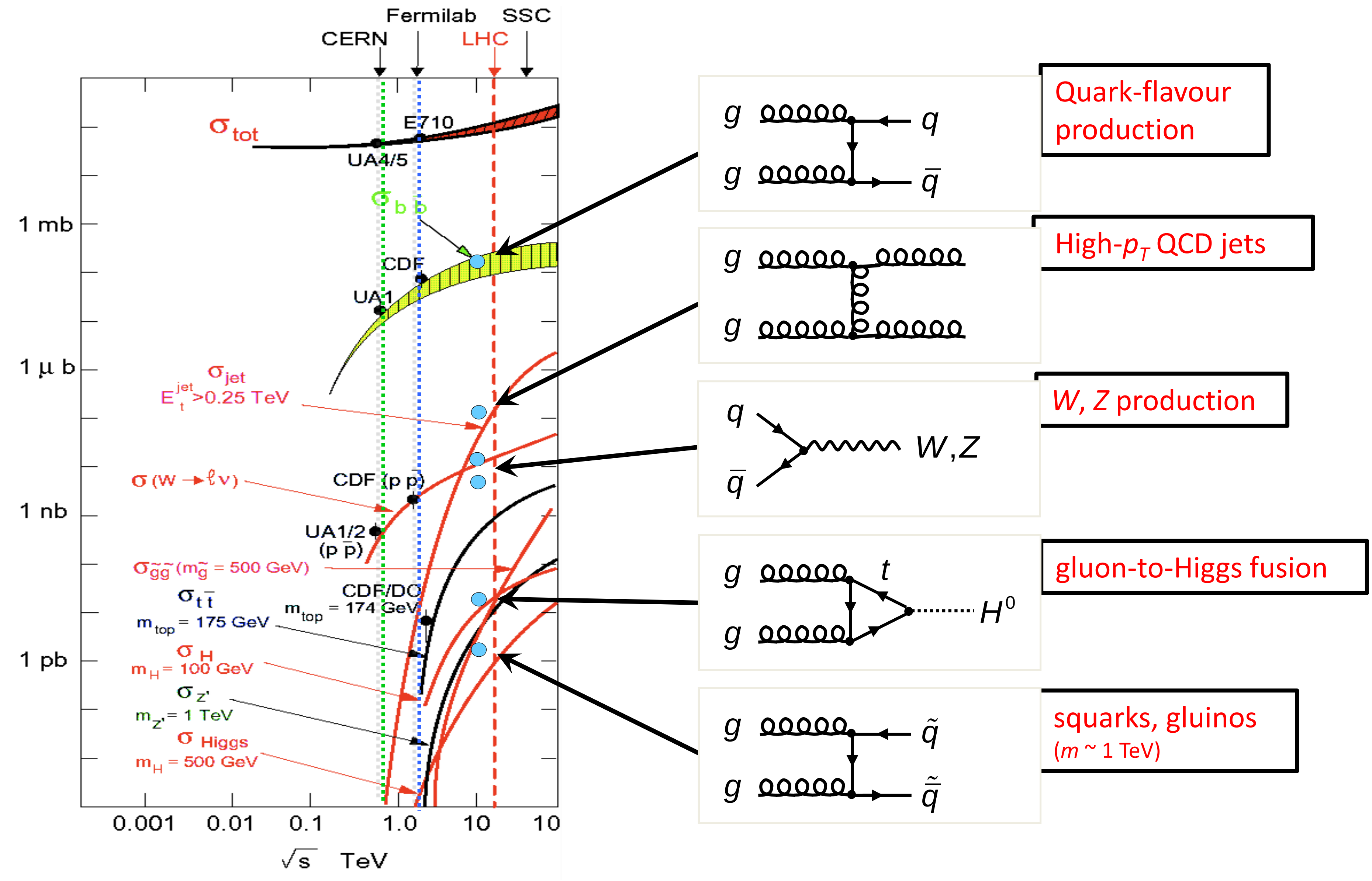


13 reconstructed vertices !

A manageble nuisance affecting
Jet, MET, and Isolation Observables

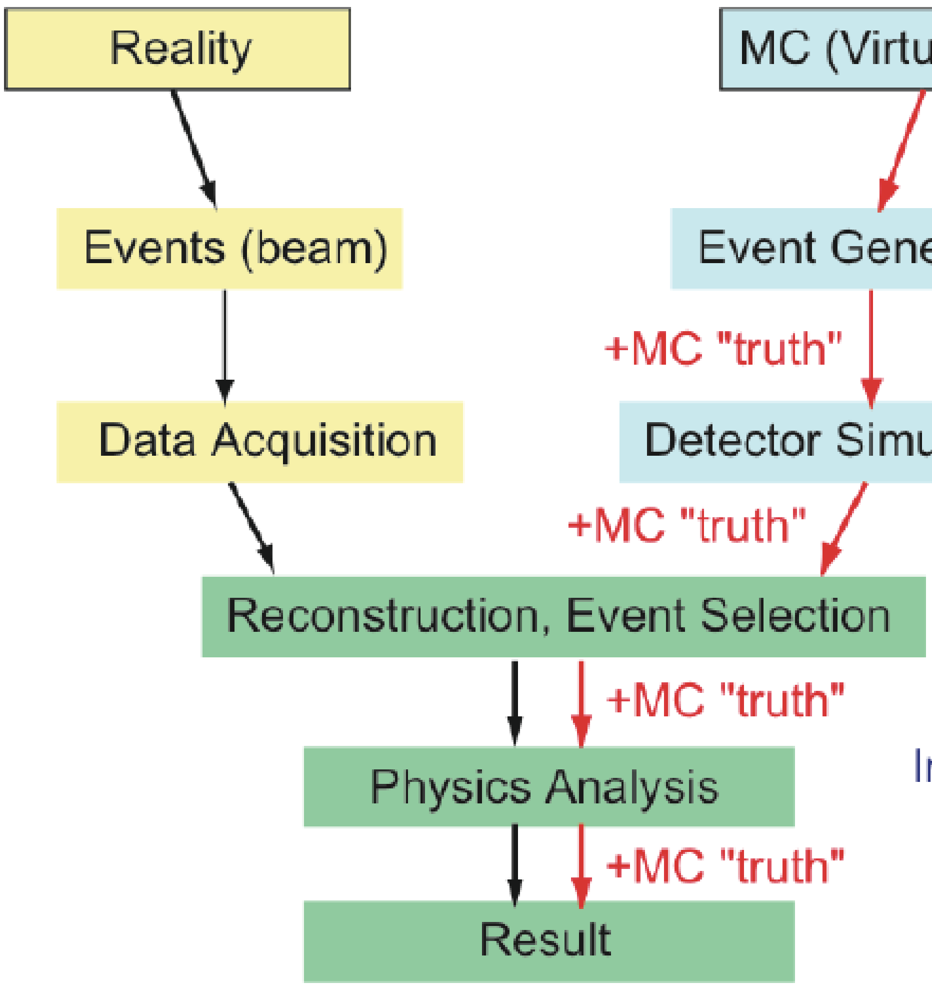
Vivek Sharma

pp(bar) Cross Sections



Hoecker

the samples processing



Generates 4-vectors for the particles, resonances, ang. dist., decays, etc. (PYTHIA, HERWIG, ALPGEN, Sherpa...)

Generates detector relevant quantities (GEANT 4)

Apply boundary conditions Acceptance

Inv. mass, efficiency, purity backgrounds, *any* dist.

Precision $\approx 1/\sqrt{N}$

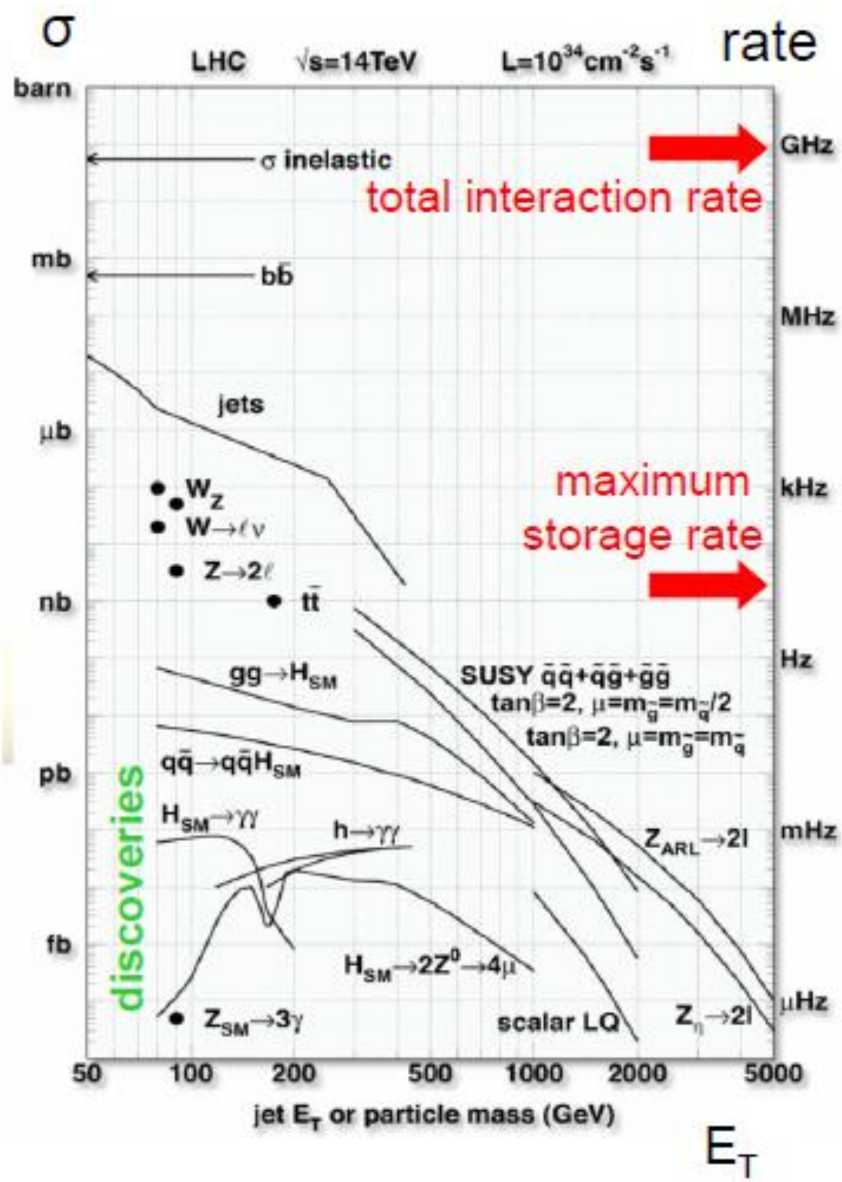
usually:

$$N^{\mathrm{MC}}_{\mathrm{signal}} \gg N^{\mathrm{Data}}_{\mathrm{signal}}$$

$$N^{\mathrm{MC}}_{\mathrm{backg}} \ll N^{\mathrm{Data}}_{\mathrm{backg}}$$ (QCD!)

R. Van Kooten, **Experimental Techniques**

Cross section and event rate



Maximum storage rate
ATLAS /CMS: about 1 kHz

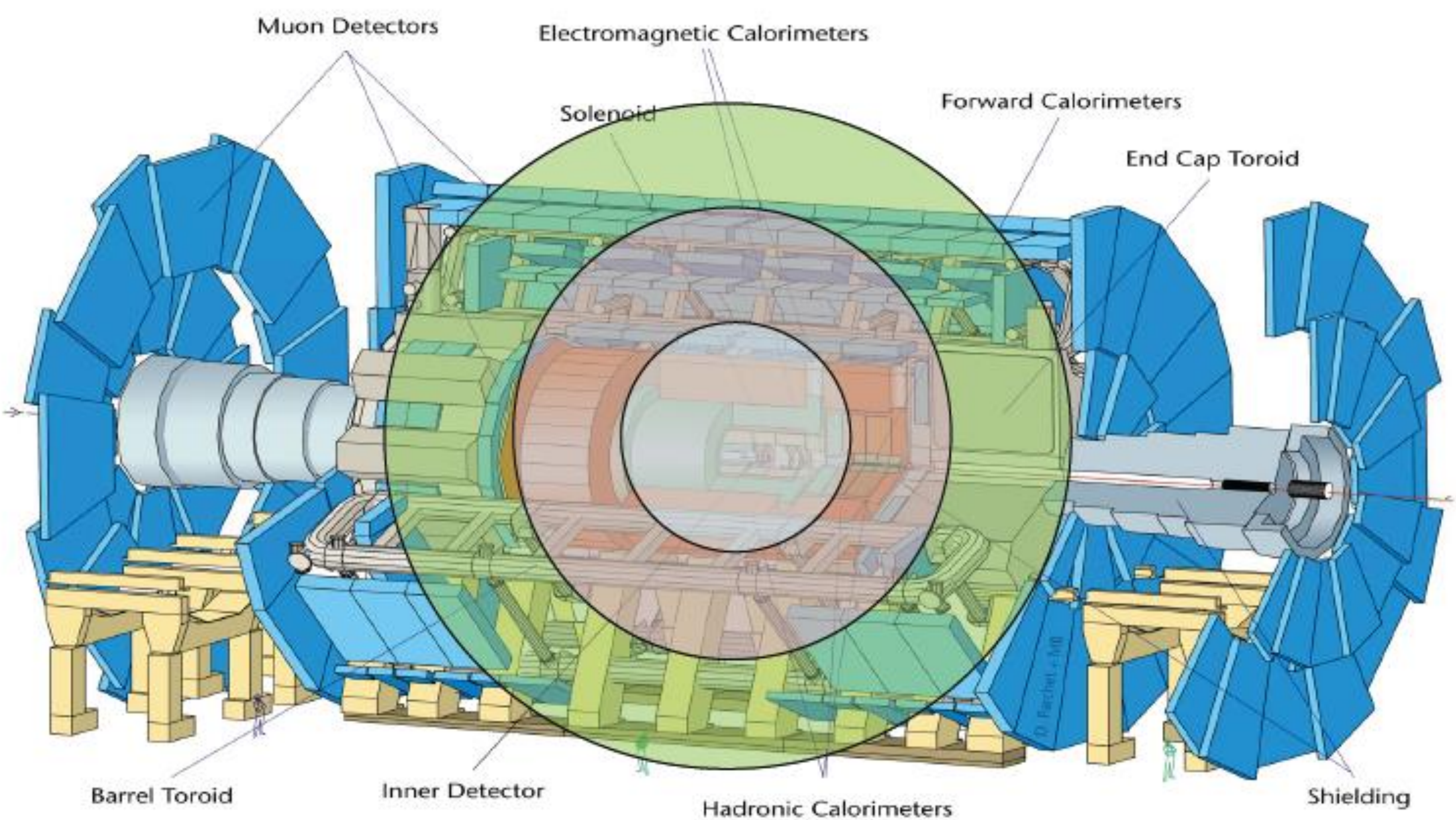
Total event rate comes in with GHz

At highest luminosities:
Up to 20 events per bunch crossing, i.e. every 25 nanoseconds ➔ GHz!

1 GHz = 1.000.000.000 events per second

Efficient **trigger system** needed for "online" event reduction
➔ Need large reduction factor

c=30cm/ns; in 25ns, s=7.5m



Few events are “inside” the detector at the same time
➔ Careful timing/synchronization needed in all components

LHC Trigger systems

Trigger is crucial, since events which are lost here are lost forever.

LHC experiments have typically a **fast hardware based trigger** level which reduces 40 MHz (bunch crossing) to 100 kHz and **a higher level software trigger** level to reduce this to the rate recorded to tape (1000 Hz)

Trigger table contains triggers on:
-electroweak particles (photons, electrons, muons, taus) , jets and missing transverse momentum at as low an energy as possible

Need to include “backup” or “monitoring” trigger for measuring the efficiencies and low p_T physics

ATLAS example
Unprescaled trigger rates at $L=1\times10^{33}$ $cm^{-2}s^{-1}$

trigger	L1 item	L1 Rate (Hz)	EF Rate (Hz)
E20_medium	EM14	8500	50
2e12_medium	2EM7	5700	1
g80_loose	EM30	700	3
2g20_loose	2EM14	750	2
mu18	MU10	5300	40
2mu10	2MU10	100	1
xe60	XE40	300	4
J180	J75	200	6
Tau29medium_xe35	TAU11_XE20	3800	6
Tau16_e15	TAU6_EM10	7500	6
J75_xe45	J50_XE20	500	10

The LHC experiments

- The LHC has two high luminosity experiments, **ATLAS** and **CMS** both aiming at a peak luminosity of $L = 10^{34} cm^{-2} s^{-1}$ for proton operation.
- There are also two low luminosity experiments:

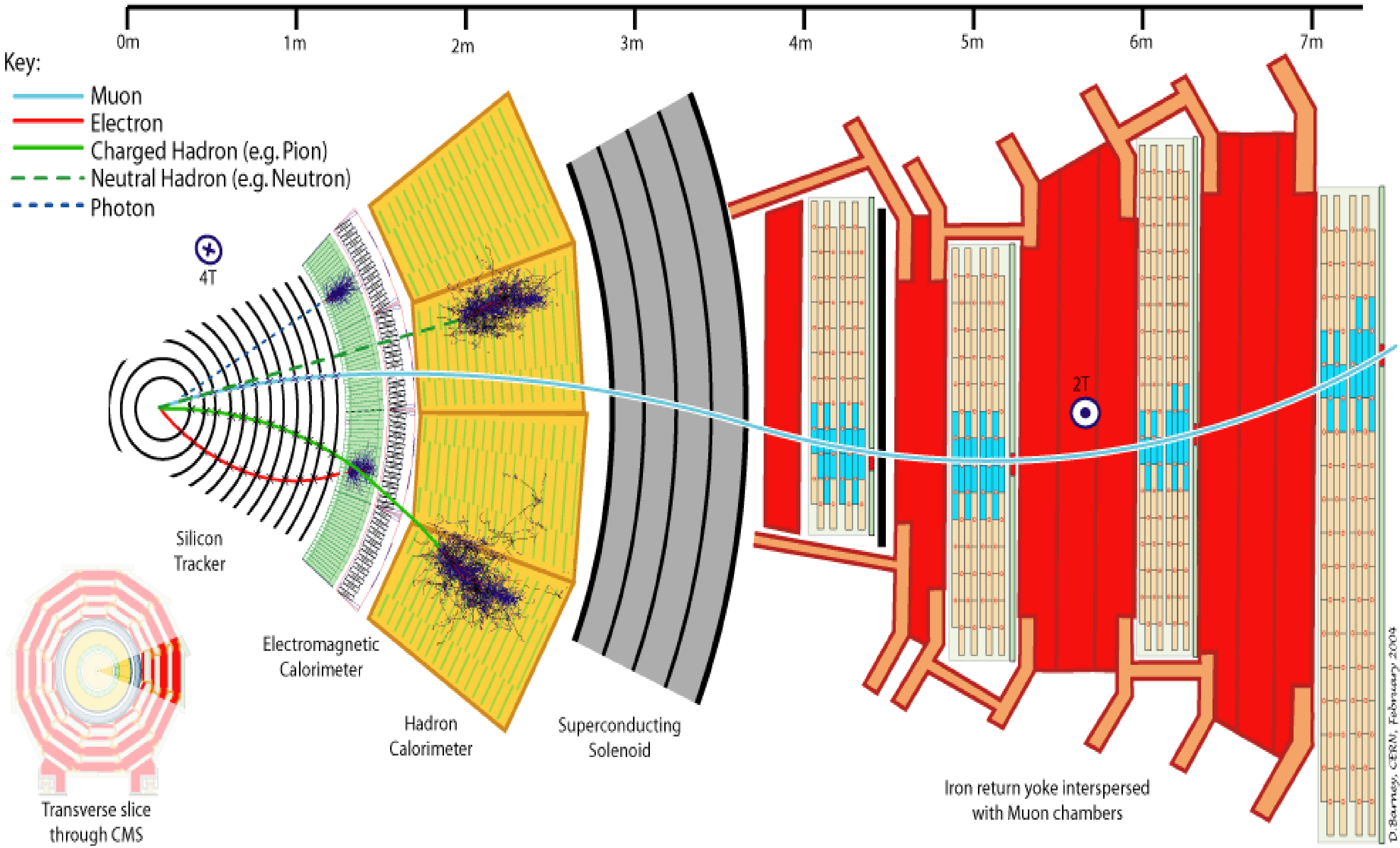
  LHCB for B-physics, aiming at $L = 10^{32} cm^{-2} s^{-1}$, and

  TOTEM inside CMS for the detection of protons from elastic scattering at small angles ($L = 10^{29} cm^{-2} s^{-1}$)
- In addition to the proton beams, the LHC will also be operated with ion beams. The LHC has one dedicated ion experiment, **ALICE** (peak luminosity of $L = 10^{27} cm^{-2} s^{-1}$ for nominal lead-lead ion operation)

LHC detectors : General features

Aim:
Multipurpose particle measurement (high p_T particles)

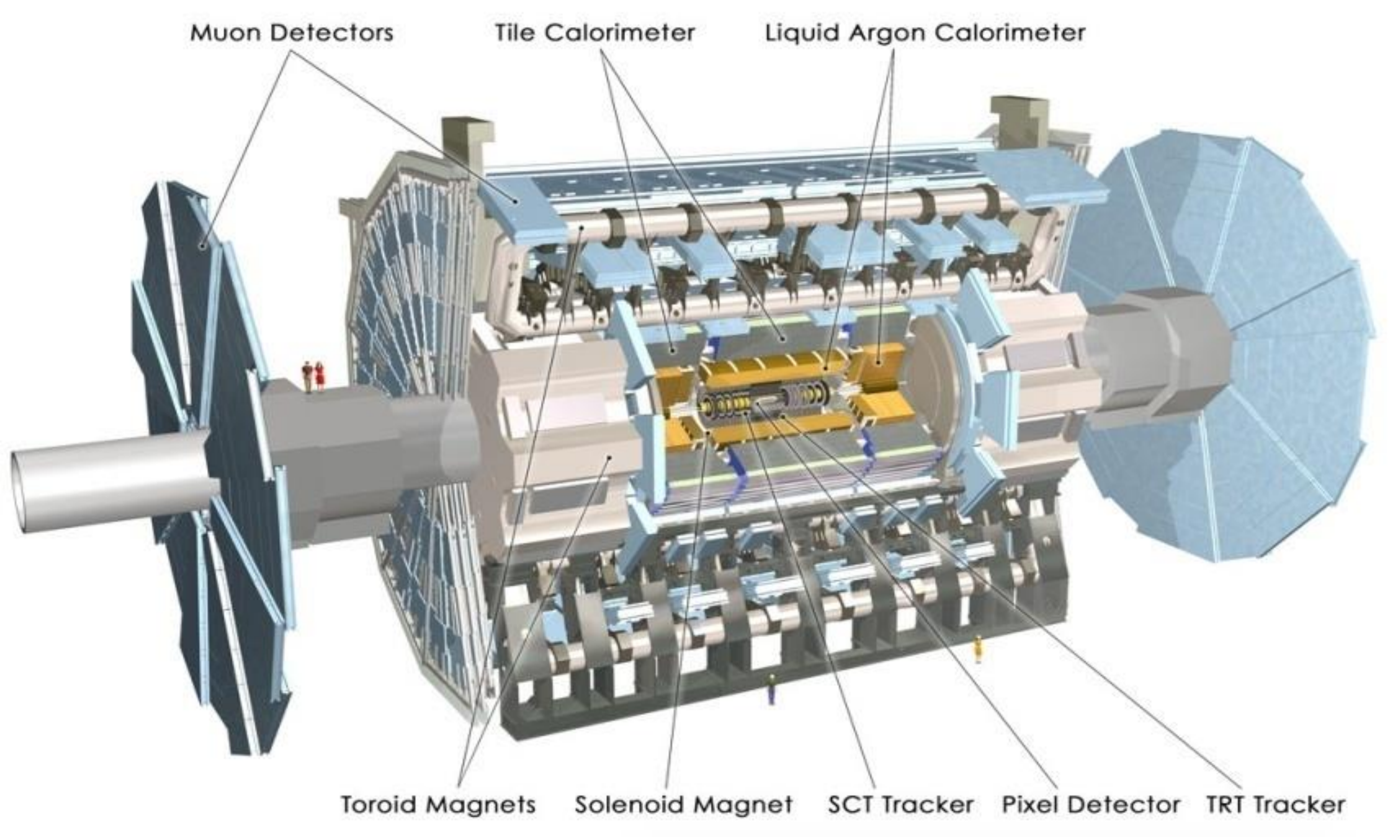
- **Tracking detectors within a magnetic field:** measures the charge, trajectory and momentum of charged particles
- **Electromagnetic calorimeter:** measures the energy and position of electromagnetic particles
- **Hadronic calorimeter:** measures the energy and position of hadronic particles
- **Muon chambers:** measures the trajectory and momentum (along with the tracking detector) of muons



Tracker EM CAL HCAL MUON CHAMBERS

The ATLAS detector

25*44 m
7000 tons



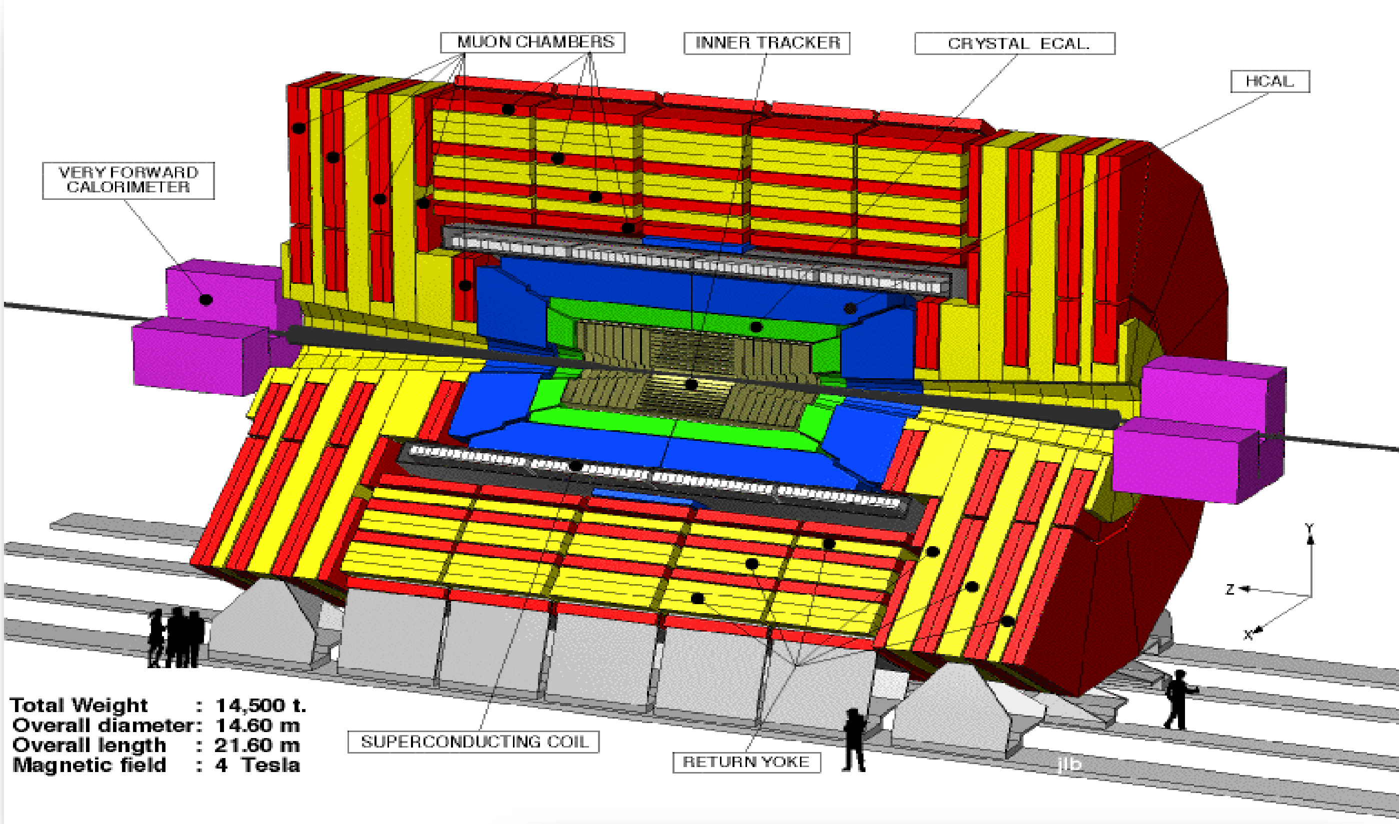
The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.

Silicon detector (pixel and strips)
and Transition Radiation Tracker (TRT)
2 Tesla solenoid + barrel and endcap toroid
Em. calorimeter (PB+Lar) :$\sigma(E)/E \sim 10\%/\sqrt{E}+0.007$
Hadronic calorimeter (Iron Tile + Scint., Cu +Lar): $\sigma(E)/E \sim 50\%/\sqrt{E}+0.03$
Muon Chambers (Drift Tubes, RPC for triggering): $\sigma(p)/p < 10\%$ at 1TeV
3 level trigger system, i.e. 2 software based HLT (L2+Event filter)

Resolutions might be measured in different experimental environments

CMS detector

15*21 m
14500 tons



The CMS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08004.

Huge silicon detector (pixel and strips)
4 Tesla solenoid
Crystal EM calorimeter: $\sigma(E)/E \sim 3\%/\sqrt{E} + 0.003$
Brass and scintillator had. Calorimeter:
$\sigma(E)/E \sim 100\%/\sqrt{E} + 0.05$
Muon Chambers (DT, CSC, RPC): $\sigma(p)/p < 10\%$ *at 1TeV with inner tracker*
Level 1 + higher level trigger

Resolutions might be measured in different experimental environments

Summary

- Part 1: Reminder Standard Model and beyond
- Part 2: Collider and detectors

Tomorrow:
Higgs, Supersymmetry, LHC searches, discussion and conclusions…

Next: Extra Slides / Particle ID

Particle Identification

Goal is to obtain **physics objects from the detector response**

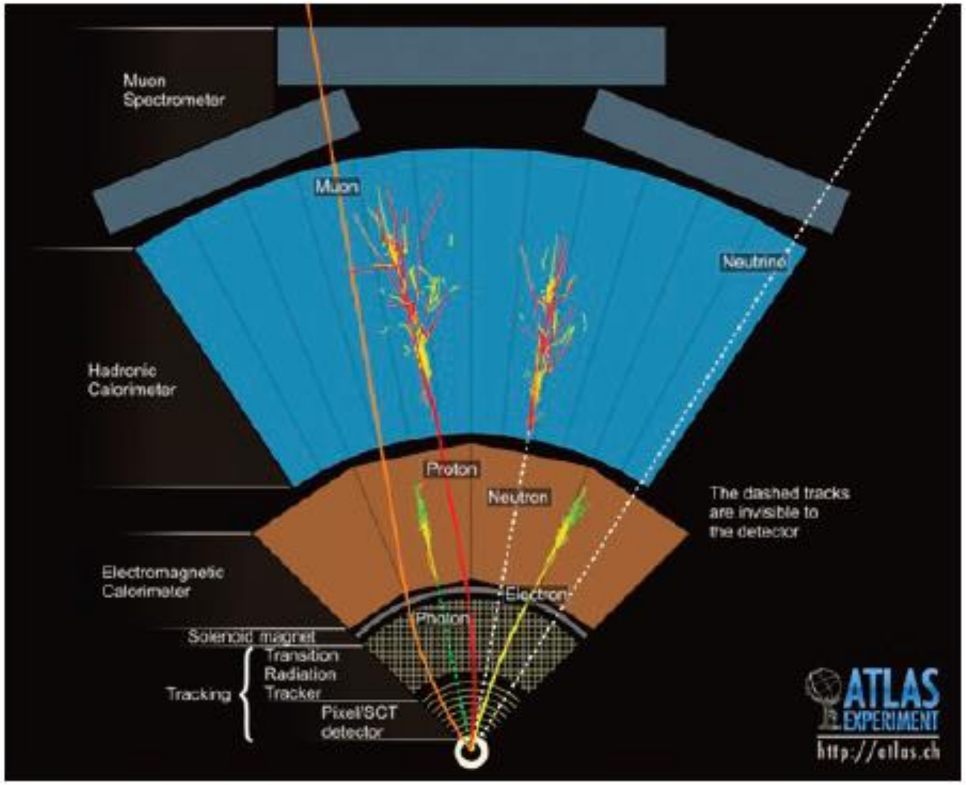
- hits in the tracker and muon detectors
- energy deposits in the calorimeters

Classification of objects is never perfect ➔ determine
efficiency = number of reconstructed&true objects / number of true objects
Purity = number of reconstructed&true objects / number of reconstructed objects

Objects reconstruction: build final objects (e.g. muons, electrons, jets) from the detector response after clustering (ATLAS, CMS)

particle-flow reconstruction in CMS: build a coherent list of stable particles and produce the analysis objects on top of them

Electron and Photon reconstruction



Photon:
- **No track** in inner detector.
- Electromagnetic shower in EM Calorimeter.
- No signal in Hadronic Calorimeter.

Electron:
- **Track** in inner detector.
- Electromagnetic shower in EM Calorimeter.
- No signal in Hadronic Calorimeter.

Muon reconstruction overview

Muon: Characteristic features:
• Minimum ionising track in all detectors (about 3 GeV energy loss in the calorimeter).
• At high momentum (few hundred GeV) bremsstrahlung in the calorimeter can be significant.
• Momentum measurement in B-field (inner detector, muon system).

High efficiency ➔ Standalone reconstruction (fit): Inner Detector or Muon System (confirmation).
High purity ➔ Combined reconstruction (fit): Inner Detector and Muon System combined.
(Also standalone and combined momentum measurement)

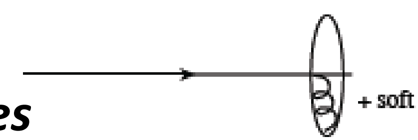
Interesting :
- Muons loose about 3 GeV in the calorimeter (MIPs)
- Momentum measurement of tracker is better at lower pt (in CMS up to 200 GeV)
- above 1 TeV significant effect of bremsstrahlung

Jet reconstruction

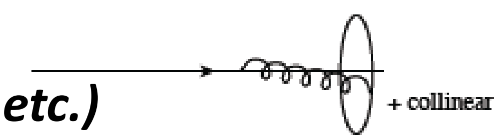
A jet is not a unique object, it is defined by the jet algorithm
→ Different choices → (Slightly) different jets
The jet algorithm is run on detector objects (clusters, tracks, combined objects) or on stable hadrons for theory predictions (or partons from NLO calculations)

Jet algorithm:
- Define a measure when to cluster/recombine close-by objects (different measures)
- Recombine the objects (different recombination schemes)

A good jet algorithm is
- ***safe to higher order effects, i.e. does not change jet quantities if a soft IR (E→0) or collinear (theta→0) gluon is radiated)***



- ***efficient and pure: jets do correspond well with partons , jets are not effected by soft physics (hadronization; pileup, etc.)***



- ***fast/simple***

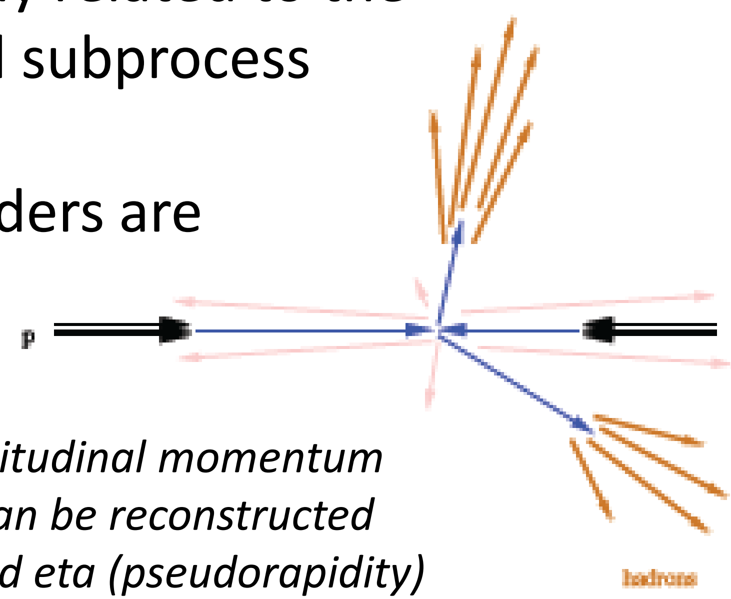
→ LHC uses not the anti kt algorithm with a R=0.4

Jet reconstruction

Initial longitudinal momentum ➔ hard system can have large boost in z-direction (but no boost in the transverse plane)
Final longitudinal momentum unknown since final state particles & beam remnant escape in beam direction

The **transverse momenta** are directly related to the hardness/energy (s_hat) of the hard subprocess

➔The (jet) variables at hadron colliders are longitudinally boost invariant :
-Differences in rapidity
-Transverse momenta
-Azimuthal angle (phi)



Initial longitudinal momentum x_1 and x_2 can be reconstructed from p_T and eta (pseudorapidity)
➔ Try it !

Jet reconstruction

CONE algorithm : - Clustering of particles in eta-phi space

- Distance measure at hadron colliders □R=sqrt(□eta^2+□phi^2)
- Cluster if R(particle,seed) < R0 + iterative + split/merging step …
- Typical CONE choices for R0 is 0.4, 0.7 or 1

Longitudinal invariant k_t algorithm (Ellis/Soper 1993)

★ Define for each protojet (hadron) $d_i = E^2_{T,i}$ and a parameter $R \sim 1$ analogous to the cone size ;

★ for each protojet pair compute:

$$d_{ij} = \min(E^2_{T,i}, E^2_{T,j})\frac{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}{R^2}$$

★ if the minimum of all d_i, d_{ij} is d_{ij}, then the protojets are merged. If the minimum is d_i, the protojet is called jet and removed from the iterations.

★ gives a list of jets with successively larger $d_i = E^2_{T,i}$, then require certain criteria:

- jet pseudorapidities should be in some range;
- jet transverse energy $> E_0$ (the lower E_0, the larger exp. and theor. uncertainties)

Jet reconstruction

CONE algorithm : - Clustering of particles in eta-phi space
- Distance measure at hadron colliders □R=sqrt(□eta^2+□phi^2)
- Cluster if R(particle,seed) < R0 + iterative + split/merging step …
- Typical CONE choices for R0 is 0.4, 0.7 or 1

Longitudinal invariant k_t algorithm (Ellis/Soper 1993)

Anti k_t algorithm (Cacciari, Salam, Soyez, 2008)

http://arxiv.org/abs/0802.1189

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2},$$
$$d_{iB} = k_{ti}^{2p},$$

with $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$

k_{ti} is the transverse momentum

For $p = 1$ one recovers the inclusive k_t algorithm

p = -1 ➔ Anti-Kt Algorithm !

$p = 0$ is the so-called cambridge/aachen algorithm

Jet reconstruction

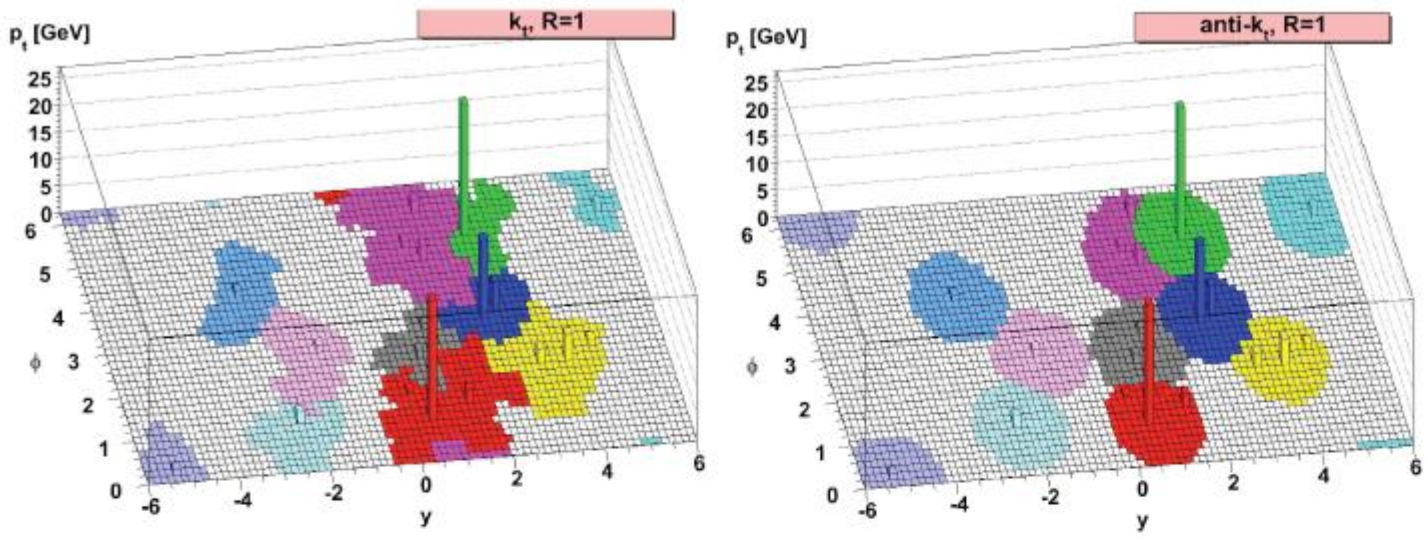


Fig. 1: Jet areas for the k_t (left) and anti-k_t (right) algorithms for $R = 1$.

- Both algorithms are IR and UV safe

Anti-Kt:

- soft particles do cluster earlier with hard particles (then among themselves)
  since minimum of distances is dominantly determined by hardest particle

➔ **Soft (low p_T) particles do not modify shape of jets (less affected by soft physics)!**

- If hard particle has no other hard neighbors it will build a perfectly round jet

Missing transverse momentum

Some particles (neutrinos, `"Dark Matter") will escape the detector without detection

Be aware : Also longitudinal momentum and energy of other final state particles escapes down the beam pipe
➔Momentum in z-direction unknown
➔Also "missing momentum" in z-direction unknown

The momentum of "neutrinos" can be reconstructed in the transverse plane
➔ It is the momentum which is missing to balance the total momentum to zero.

Define: transverse energy vector

$$\boldsymbol{E}_T^{\text{miss}} = -\sum_i \boldsymbol{p}_T(i)$$

where the sum runs over the transverse momenta of all visible final state particles.

The "norm" of this vector is the **missing transverse momentum**

Missing transverse momentum

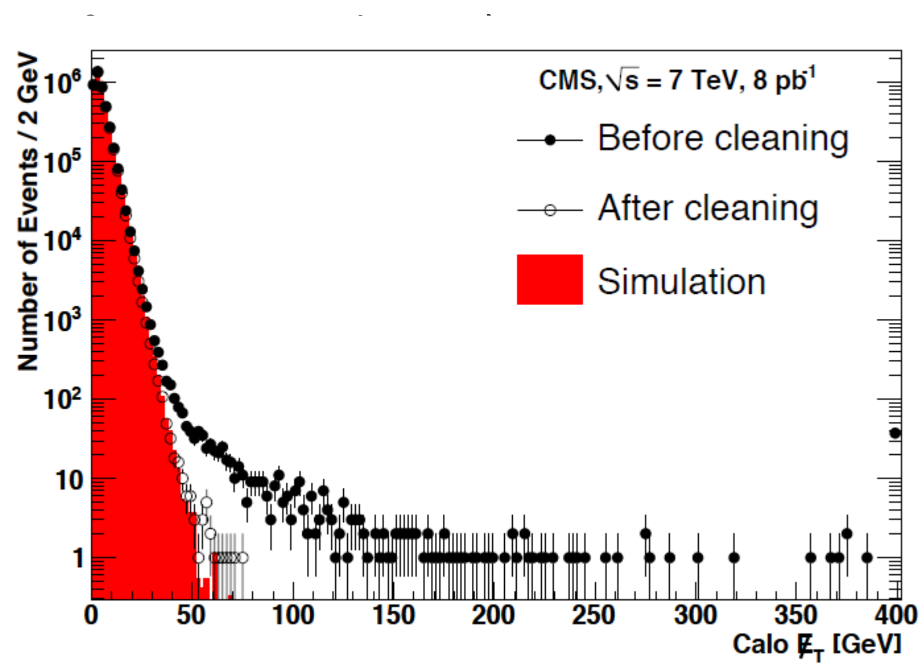
The performance of the measurement of the missing transverse momentum depends on the measurement of ALL other particles in the sum.

Measurement is affected by:

- Noise effects, mis-calibrations, various calorimeter problems (dead channels, …)
- Modeling of QCD background events, pile up, multiple interactions, …
- muon momentum measurement (be awa
- overlaid cosmic background events
- beam halo (collisions upstream of detector, events parallel to beam)
- …

Important variable :
ETmiss significance
How likely is the seen Etmiss value ?

Naive: $\Sigma = \not{E}_{\mathrm{T}} / \sqrt{\sum E_{\mathrm{T}}}$



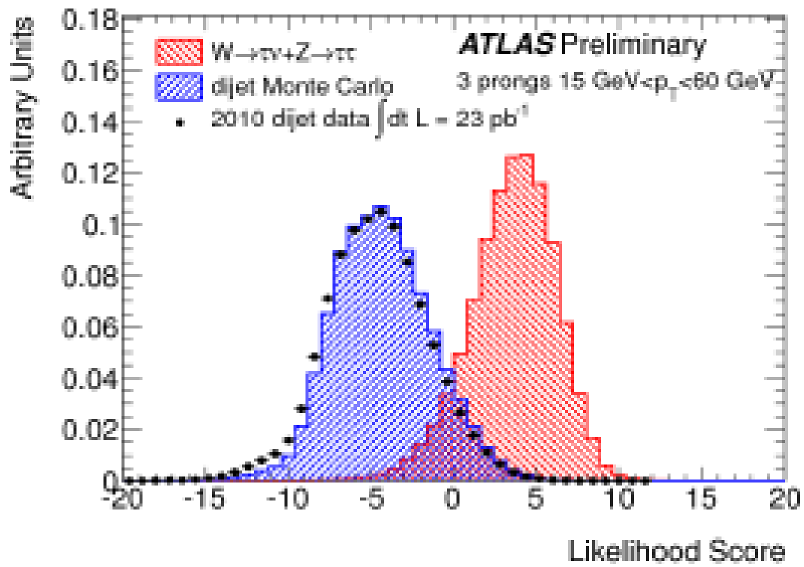
Tau identification

Tau decay 70% hadronically ➔ Tau Identification algorithm
(leptonic decays visible as electron or muon + missing momentum)

Reconstructed as a narrow electromagnetic jet with small number of tracks
(➔ background from electrons)
Sum of particles inside jet compatible with tau decay

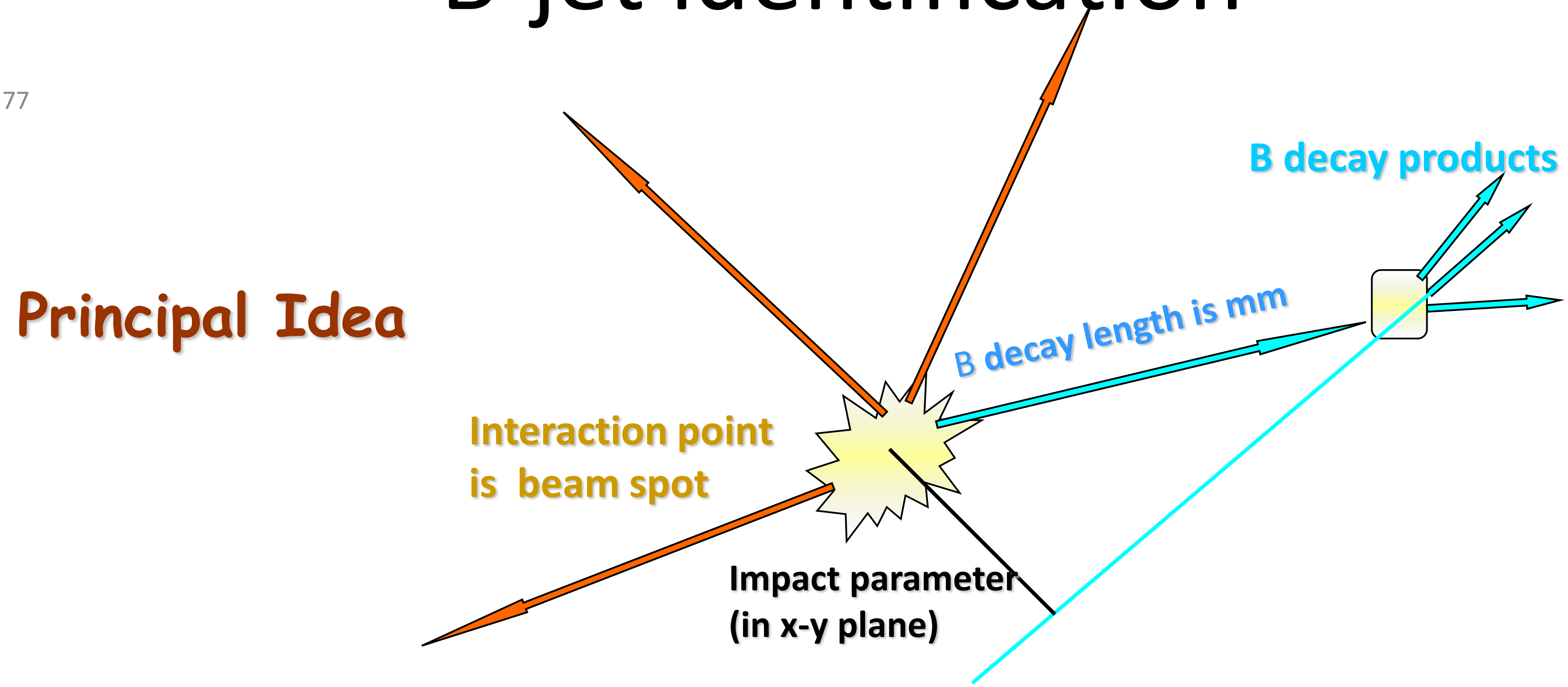
➔Tau / Jet separation:
-Transverse shower shape variable
-Tracks
-Mass of decay product

Variables are correlated
➔Use multivariate classifiers
(projective Likelihood, Neural Networks, Decision Trees, etc.)
for classification
+ separation against electrons…
(longitudinal shower shapes)



Discrimination performance (likelihood tagger)

B-jet identification



B-jets tagging algorithm examples

-Build likelihood from track impact parameters belonging to the jet

-Reconstruct the B-hadron decay vertex

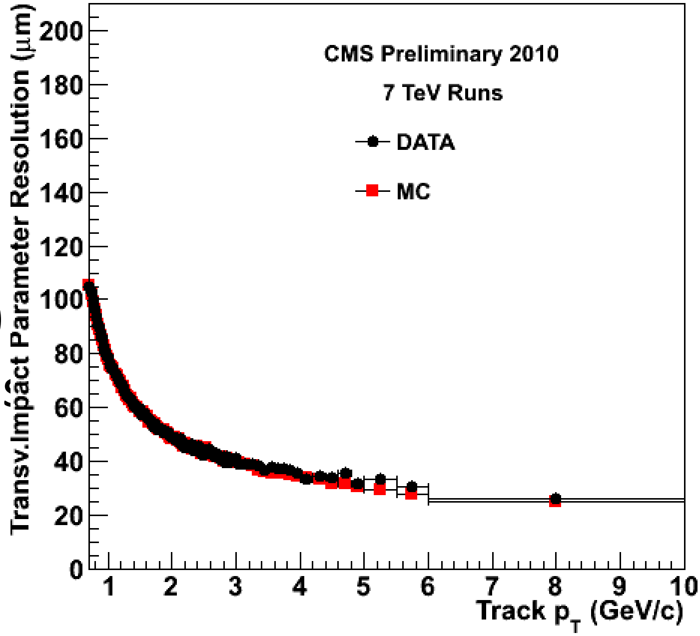
-Reconstruct B-hadron decay products (lepton decays, muon)

-Combination e.g. via a Neural Network

Measuring primary vertices and b-tagging

Tracker also needs to be able to do precision vertexing to:

- Distinguish between signal and pileup vertices
- Identify secondary vertices (or at least displaced tracks) to do b-tagging.



The figure-of-merit is the impact parameter resolution which improves as:

- p_T increases (less effect from multiple scattering)
- material is reduced, especially between innermost measurement and interaction region (less m.s.)
- distance between innermost measurement and interaction region decreases (less extrapolation)

Particle ID matrix

True → Reconstr.	jet	electron	muon	photon	B-jet	tau
Jet (reco)	0.99	1-electron effi.	sometimes	often	large	large
electron	small	0.7-0.8	small	sometimes	small	large /DECAY
muon	sometimes	small	about 0.9	small	sometimes	Large /DECAY
photon	large	large	small	0.7-0.8	small	small
B-jet	large	small	small	small	0.5	large
Tau	large	large	small	small	sometimes	0.5

Extra Slides

Low p_T events – "names"

- **Multiple Interactions**

  Partons of the protons can lead to multiple interactions within the same proton (remnant-remnant interactions) and also low p_T initial/final state radiation, not luminosity dependent

- **Pile up events**

  Luminosity dependent, events from the same bunch crossing, happens more often if size of bunch is smaller

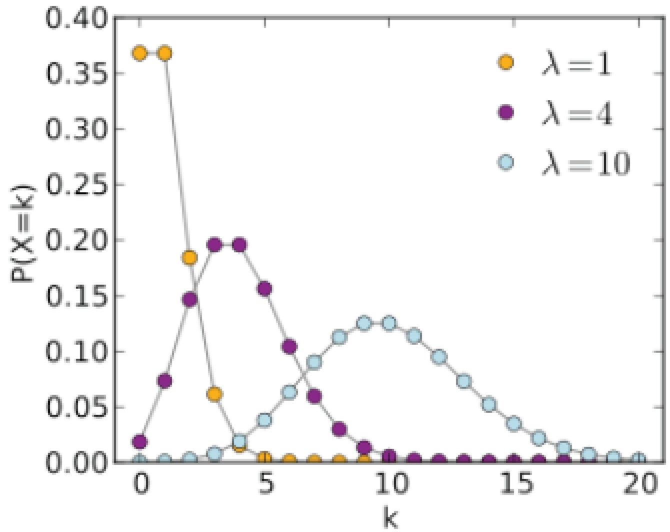
- **Minimum bias events**

  Events recorded with no trigger bias, low p_T QCD events from totally inclusive pp cross sections

  Calculated partly with exchange of color-neutral objects (pomeron, diffraction) ➔ more tomorrow

  ➔These events are used to "model" pile up events

Pile up



- given an average number of interactions, the number of PU events per bunch-crossing is expected to have roughly a poissonian distribution

Determine number of Pile up (PU) Events:

multiply the luminosity (per bunch) by the minimum bias cross-section (71.3 mb) gets the expected rate per bunch:

(do not multiply with the number of bunches in the lumi normula seen before)

$$\mathrm{Rate}_{\mathrm{pileup}_{\mathrm{xing,ls}}} = \mathscr{L}_{\mathrm{xing,ls}} \cdot \sigma_{\mathrm{minimum\ bias}}$$

divide by the revolution frequency of a bunch to get the number of PU events:

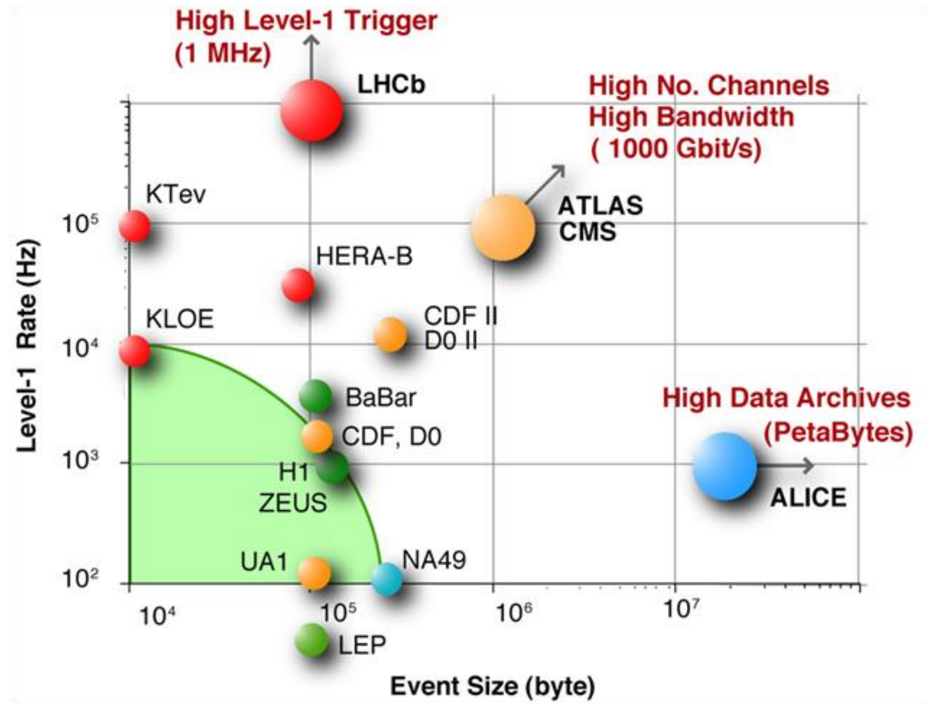
Prob. To see N pile up events in one bunch crossing

$$\mathscr{N}_{\mathrm{pileup}_{\mathrm{xing,ls}}} = \frac{\mathscr{L}_{\mathrm{xing,ls}} \cdot \sigma_{\mathrm{minimum\ bias}}}{\mathrm{cirulation\ rate}}$$

calculate average distributions over longer periods, weighting by the luminosities

LHC Computing model

4 LHC experiments *
large number of channels * high rate
➔15 Petabyte of data produced each year
➔Tiered computer model needed (The Grid)
➔340 k of (today's) fastest CPU cores
➔45 PB of disk storage



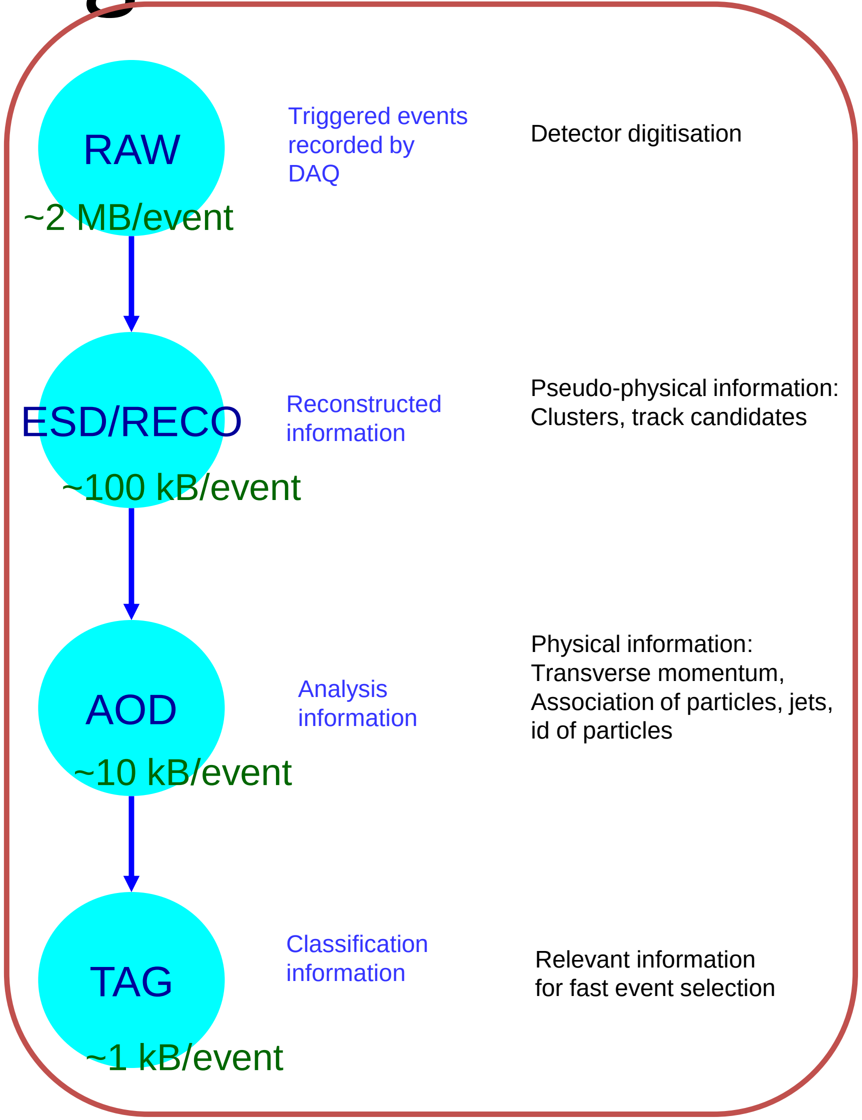
The HEP community and funding is distributed
Significant computing was available in many institute

LHC computing model

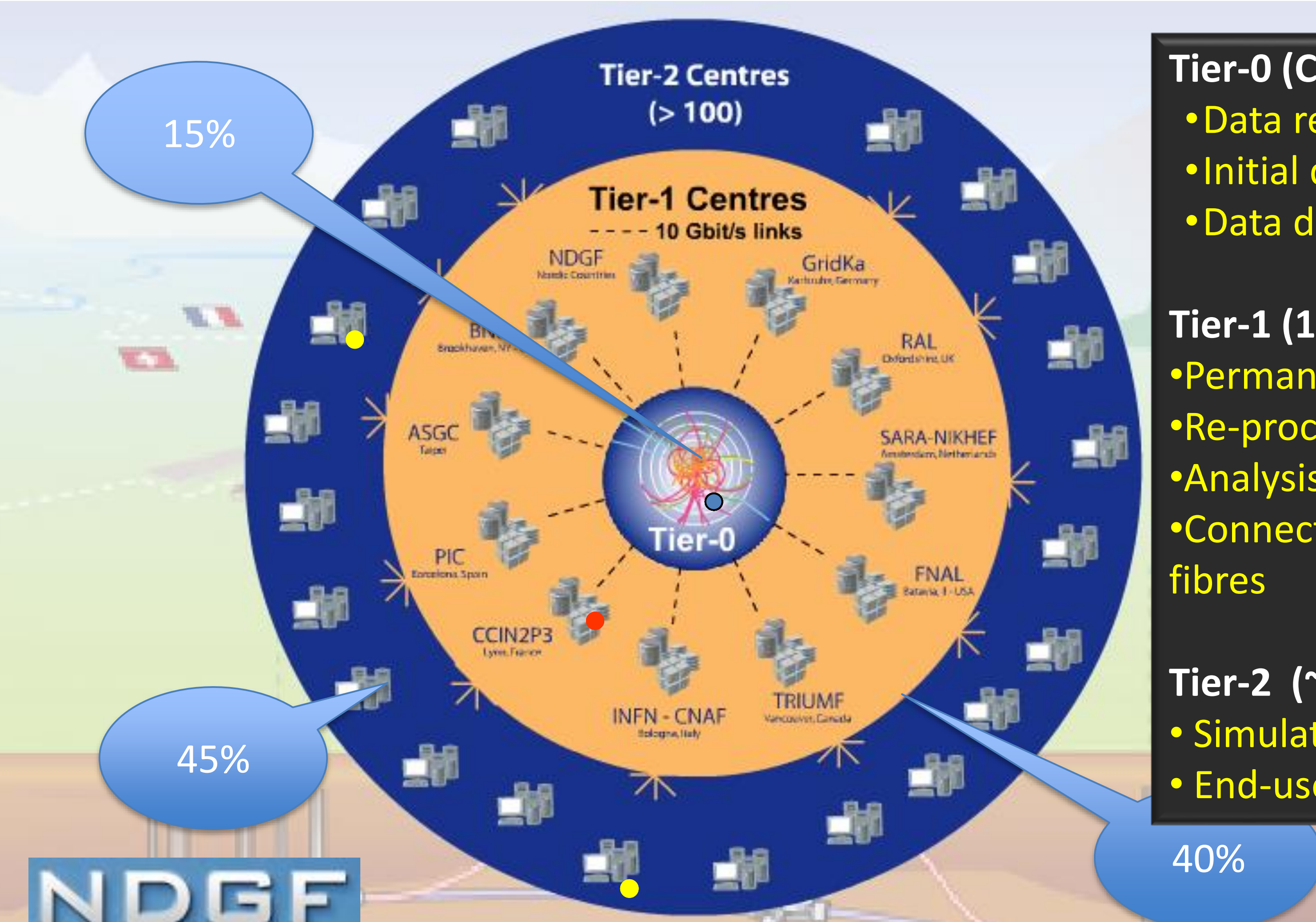
- HEP data are organized as *Events* (particle collisions)
- Simulation, Reconstruction and Analysis programs process

“one Event at a time”

➔ Information “Clustering”



Schulz



Tier-0 (CERN): (15%)
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (11 centres): (40%)
- Permanent storage
- Re-processing
- Analysis
- Connected by direct 10 Gb fibres

Tier-2 (~200 centres): (45%)
- Simulation
- End-user analysis

Pile up

Effects on the measurement:

Energy from the additional min bias events added to the "interesting" event

➔ More hits, tracks, energy deposits not belonging to "interesting" event

Note that the min. bias events are predominantly! at low p_T and do not happen at the same vertex

How to deal with Pile up ?

-Pile up effects are included in the simulation

-Precise vertexing, ask jets etc. to come from primary vertex

-Subtract pile up energy in isolation cones (for "pile up" events)

- ....